Proceedings of the Open University Geological Society

Volume 1 2015
Including Marine Geotales Symposium 2014 and OUGS Members' articles, and the Annual Report for 2014

Editor: Dr David M. Jones
41 Blackburn Way,
Godalming, Surrey GU7 1JY
e-mail: proceedings@ougs.org

The Open University Geological Society (OUGS) and its Proceedings Editor accept no responsibility for breach of copyright. Copyright for the work remains with the authors, but copyright for the published articles is that of the OUGS.

ISSN 2058-5209
© Copyright reserved

Proceedings of the OUGS 1 2015; published 2015; printed by Hobbs the Printers Ltd, Totton, Hampshire

Committee of the Open University Geological Society 2014–15

Society Website: ougs.org

Executive Committee

President: Dr Tom Argles, Department of Earth Sciences, The Open University, Milton Keynes MK7 6AA; president@ougs.org
Chairman: Linda Fowler; chairman@ougs.org
Secretary: Don Cameron; secretary@ougs.org
Treasurer: John Gooch; treasurer@ougs.org
Membership Secretary: Phyllis Turkington; membership@ougs.org
Newsletter Editor: Lyn Relph; news@ougs.org
Information Officer: Pauline Kirtley; info@ougs.org

Branch Organisers

East Anglia (EAn): Richard Kirkham; east.anglia@ougs.org
East Midlands (EMi): Sue Atkinson: east.midlands@ougs.org
East Scotland (ESc): Stuart Swales; east.scotland@ougs.org
Ireland (Ire): Susan Pyne; ireland@ougs.org
London (Lon): John Lonergan; london@ougs.org
Mainland Europe (Eur): Elisabeth d'Eyrames: mainland.europe@ougs.org
Northumbria (Nor): Paul Williams: northumbria@ougs.org
North West (NWe): Jane Schollick: north.west@ougs.org
Oxford (Oxf): Sally Munnings; oxford@ougs.org
Severnside (Ssi): Janet Hiscott; severnside@ougs.org
South East (SEa): Elizabeth Boucher; south.east@ougs.org
South West (SWe): Rich Blagden: south.west@ougs.org
Walton Hall (WHa): Mrs Burti Montagu-Leon; walton.hall@ougs.org
Wessex (Wsx): Sheila Alderman; wessex@ougs.org
West Midlands (WMi): Sandra Morgan; west.midlands@ougs.org
West Scotland (WSc): Cliff Probert; west.scotland@ougs.org
Yorkshire (Yor): Ricky Savage; yorkshire@ougs.org

Other officers

(non-OUGSC voting)
Sales Administrator: John Lonergan; sales@ougs.org
Minutes Secretary: Linda McArdell; minsec@ougs.org
Journal Editor: Dr David M. Jones, 41 Blackburn Way, Godalming, Surrey GU7 1JY; journal@ougs.org
Archivist/Reviews: Jane Michael; reviews@ougs.org
Webmaster: Stuart Swales; webmaster@ougs.org
Deputy Webmaster: Martin Bryan:; webdeputy@ougs.org
Gift Aid Officer: Ann Goundry; giftaid@ougs.org
Branch Organisers Representative: Jane Schollick: borep@ougs.org

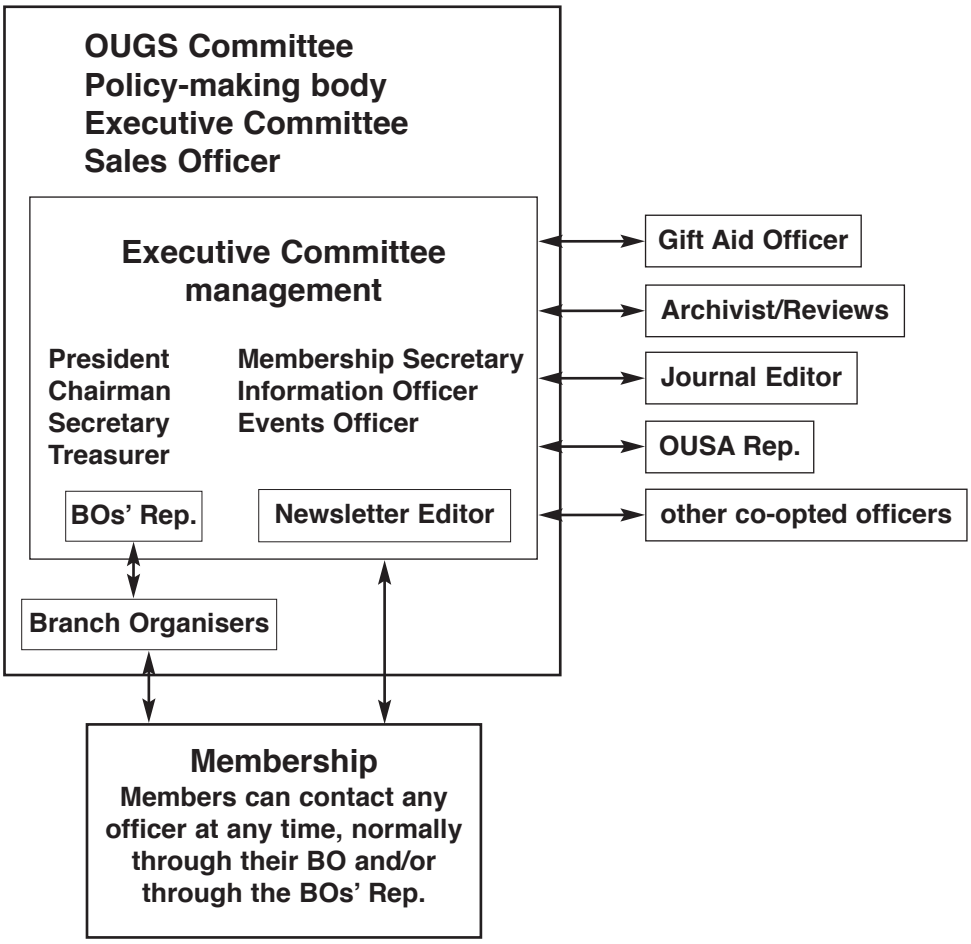
Vice Presidents

Dr Evelyn Brown, Dr Michael Gagan and Norma Rothwell: normarothwell@gmail.com

Past Presidents

1973–74 Prof. Ian Gass
1975–76 Dr Chris Wilson
1977–78 Mr John Wright
1979–80 Dr Richard Thorpe
1981–82 Dr Dennis Jackson
1983–84 Prof. Geoff Brown
1985–86 Dr Peter Skelton
1987–88 Mr Eric Skipsey
1989–90 Dr Sandy Smith
1991–92 Dr Dave Williams
1993–94 Dr Dave Rothery
1995–96 Dr Nigel Harris
1997–98 Dr Dee Edwards
1999–00 Dr Peter Sheldon
2001–02 Prof. Bob Spicer
2003–04 Prof. Chris Wilson
2005–06 Dr Angela Coe
2007–08 Dr Sandy Smith
2011–12 Dr Dave McGarvie
2012–13 Dr Nick Rogers

DISSEMINATION OF INFORMATION PATHWAYS



Editorial:

Dear readers,
This issue launches our publication under its new title:
Proceedings of the Open University Geological Society.

The Proceedings *(*POUGS*) will henceforth be a combined publication containing articles and book reviews, as the* OUGS Journal *did, and the* OUGS Annual Report *in one binding. There will be one main issue each year, occasionally followed by a 'Supplement' with OUGS Members' articles later in any given year if a sufficient number of articles are received.*

POUGS *will comprise articles from the previous summer's OUGS Symposium, OUGS AGM Keynote and Geoff Brown Memorial Lecture articles, articles by OUGS Members on branch field trips, individual geological studies, seminars and exhibitions, and book reviews.*
...The Annual Report *will be a separately numbered section at the back, and will comprise the AGM Minutes from the previous year's AGM, Officer and Branch Organiser reports, the OUGS Constitution (up-dated as appropriate) and the* OUGS Journal *Index (to which articles from subsequent* Proceedings of the OUGS *will be added each year, as usual).*

This first volume of the POUGS *has ten articles from the 2014 OUGS Symposium held in Canterbury. The theme was oceanography, under the title 'Marine Geotales'. We have articles on the Holocene evolution of the Norfolk Banks; an analysis of the chemistry of the ocean past and present; the significance of the humble bubble for climate and weather (involving someone/thing named 'Bob'; the exploration and mapping of the ocean floor in minute detail; the analysis of and effective reactions to coastal ecology and disaster risks; oil and gas exploration in the Arctic and its implications; a tour of Kent's coastal geology, with some archaeology and history thrown in; some analyses of and lessons learned from tsunamis and submarine earthquakes; and the Quaternary palaeogeography and evolution of the North Sea Basin and the English Channel. All nicely summed-up by OUGS President Tom Argles.*

From OUGS Members we have an interesting selection revealing the varied interests of our fellow geologists. There are field trip reports on ophiolites in Scotland (Ballantrae) and in Cornwall (The Lizard — including 'lizard skin' serpentinised — get it? — peridotite); a trip through the French and Italian Alps examining the tectonics, lava tubes and an impressive leaning 'wall of ammonites'; the geology of the Severn estuary and its 'Crossings'; the cyclothems and glacial-formed topography of the Cliviger Valley; the geology of the Mourne-Cooley-Gullion Geotourism Project (including a smuggler's head and a geological conundrum no less!); and a marvellous, not-to-be-taken-for-granted shopping-centre tour of lovely polished granites, marbles and limestones in Dundrum, Dublin. Our new publication concludes with a fluent report on the 'Jurassic Ark' exhibition at the Bath Royal Literary and Scientific Institution.

As always, I wish you happy reading.
— David M. Jones, OUGS Proceedings Editor

Errata

Apologies, readers!
OUGS Member Rosemary Darby — whose eagle eye is clearly as keen as ever! — has spotted a couple of oddities in *OUGSJ* 35 (1–2) 2014:

page 7, right column, line 11: 'there hinterlands' should be 'their hinterlands'.
page10, right column, line 19: 'Probably' should be 'Probability'.
page 11, left column, line 25: 'the use a large vessel' should be 'the use of a large vessel'.
page 17, photo caption. The caption has 'Jim Robbins', whereas the reconstruction is actually signed 'Robins'. Interesting! Here is the actual caption sent to me (which I copied and pasted into the layout, failing to spot the discrepancy!): "*Scientifically accurate artist's reconstruction of the original colours of Sinosauropteryx based on fossilised melanosomes. Copyright University of Bristol / Jim Robbins*". My bad!
page 44, left column, line 8: 'know' should obviously be 'known'.
page 53, left column, penultimate line: 'Westoll's' should be the 'Westolls' '.
page 56, right column, 11: 'he and' should be 'and he'.
page 57, for which I apologise profusely to Gill, I have somehow let the final 'y' in 'Toney', her surname, drop out in the title page and in the Contents list; also in the captions to Figs 20 and 21. Fortunately, it is correct in the text with the byline for her contribution to the report!
page 95, right column, line 7: 'period limestone reef' should be 'period, forming the limestone reef'.

I really do apologise for so many slips. Must schedule more time for another proofreading! — Ed.

OUGS Symposium, Canterbury 2014: Marine Geotales

Tales from the deep blue sea: detecting earth processes from marine sedimentary processes

Dr Angela L. Coe

(Senior Lecturer in Earth Sciences, The Open University)

Dr Coe gave the keynote address on Friday evening. She spoke about a range of topics, including sea-level change, de-oxygenation, weathering, productivity using fossils, marine sediments and geochemistry. (Because Dr Coe presented much new data to be included in imminent publications by her and her doctoral students, we honoured her request that we not record her talk — Ed.)

Holocene evolution of the Norfolk Banks

Dr Peter S. Balson

(Principal Scientist in Coastal Geosciences, BGS, Keyworth, Nottingham)

[Unfortunately Dr Balson was unable to write up his lecture for the *OUGS Proceedings* or to edit the transcript of his recording that was sent to him in November 2014. Therefore we are publishing his abstract from the Symposium brochure and the transcript prepared from the recording of his lecture.]

Abstract

The Norfolk Banks have long been regarded as typical examples of modern tidal sand ridges found on the world's continental shelves. Their asymmetric cross-sectional profile and internal structure indicate migration perpendicular to their long axis, and in an offshore direction. It is, however, difficult to demonstrate whether or not such migration occurs now, and at what rate. Observations of water movement, sand-wave asymmetry and sand tracers support a component of offshore sand transport. Shallow seismic refection data enable a clearer determination of the internal geometry of some of the Norfolk Banks. These data confirm the unidirectional nature of the dipping internal reflectors first noted by Houbolt (1968), which contrasts with the structures observed within sandbanks elsewhere in the North Sea. The new data enable reconstruction of the relationship between the sandbank and the underlying topography, and the determination of the volume of sediment within the banks. This volume can be placed into the context of the long-term sediment budget for the area, and a model for the Holocene evolution of the Norfolk Banks is proposed. The Norfolk Banks are compared to bank systems elsewhere in the North Sea, which differ in terms of their grain sizes, sand transport patterns or evolutionary history.

[OUGS Canterbury Symposium: Marine Geotales; original transcription by Sara Osman from the seminar recording; edited (mainly for house style and text flow) by POUGS Editor David M. Jones]

[Introduction]

[The Norfolk Banks are] internationally widely regarded as one of the classic examples of sand banks. Because of that, when you see standard textbooks about sand banks, Norfolk Banks are always mentioned. So the question is: Are they really typical? Are they really a model for sand banks everywhere?

OK, so what I am going to do first? [The plan is] to talk a little about what tidal sandbanks [are] as opposed to wave-generated sand banks: How do they form? Why are they important? Why should we be studying them? Why are we interested? Then some information about the Norfolk Banks, how the Norfolk Banks fit into a story of Holocene sea-level rise and sand bank evolution, [followed by] a quick review of some of the conceptual models that have been proposed for describing how they respond, and then a few conclusions.

[What are sand banks?]

What are tidal sandbanks specifically? They are large bodies of sand, clearly. And they are found on many continental shelves in the world, but only where there are very strong tidal currents — 0.9m s^{-1} to 8m s^{-1}? Now the example of 8m s^{-1} is up in the Pentland Firth, so is exceptional. So the range is [typically] probably *c.* 0.9m s^{-1} to *c.* 2m s^{-1}. They can be tens of kilometres long — very large features indeed on the shelf. They are oriented sub-parallel to the dominant tidal current direction. So they are not like sand waves or dunes, which would be oriented across the dominant current direction, at right angles. They are mobile; some of the ones in the near shore areas are very mobile, ones in offshore settings tend to be less mobile. But they may have some of these smaller transverse features, called sand waves, on their surfaces. And they may be important in the way [that] the sand banks are formed and the way that they evolve.

Now in the literature there have been a number of classifications. Geologists love to classify things when they see them and there have been a number of classifications of sand banks. Sand banks are actually quite complex and it's difficult to classify them, but this is a fairly straightforward classification, proposed by Stride in the [19]80s, of just two types: active and moribund. And that's going to be important in what we are talking about here.

Active sand banks are those that are moving; they are maintained by the present-day sand transport and so you often get sand waves on them. [T]he second category is important in the Holocene context, called moribund sand banks. [T]hey appear to no longer be being maintained by present-day sand transport,

© OUGS ISSN 2058-5209

so [they] could be regarded as relict. They possibly relate to a former sea level, when sea level was lower. But when sea level rose, perhaps the currents reduced and they became static, and, if you like, 'fossils'; and sand waves tend to be absent [—] we'll come back to [this] again towards the end of the talk.

[Sand bank models]

As I said, we are going to review four different types of model [— that is] conceptual models —of how sand banks came about. [A] lot of these [models] seem to be quite old: [19]68 to [19]82, and that's not because sand bank science hasn't moved on, but is because of this quite difficult idea of having one size fits all. [P]eople now, I think, are perhaps a bit more sophisticated in the way they think about geomorphological behaviour and so there isn't a single model. But we'll [also] come back and review those towards the end [of the talk].

[Recent interest in sand banks]

Now there's been a resurgence in interest in sand banks in the last ten years. And why is that? Why are sand banks suddenly so important to us, when perhaps before they were just of academic interest? So why *are* they of interest? Well, we [have known] for centuries [that] sand banks [are] a hazard to navigation. Ships have run into them and been lost. Channels move and that's because sand banks are essentially mobile features. [W]e've got a lot of shipwrecks on sand banks, so there is a great interest in knowing where they are, charting them so that we can avoid them when we are moving our ships around. As I say, that's been going on for centuries. And because of that there has also been a resurgence in the interest in maritime archaeology, because [sand banks] effectively represent somewhere where you are likely to find a wreck. And because sand banks move about, sometimes opportunities arise, something is revealed and we find a new wreck that we didn't know was there.

I have a few examples here — these are all local examples by the way, for Kent. We've got *Radio Caroline* on the Goodwin Sands from a few years back; we've got a shipwreck on a sand bank just off Margate; and we've got the recent discovery and recovery of the *Dornier 17* off the Goodwin Sands, which has been in the press quite a lot.

So, again maritime archaeology. Now the unfortunate captain of the ship at the top [presumably being pointed out by Dr Balson on a PowerPoint slide (hereafter PP)], a ship called the *Hindostan*, ran aground just off Margate during a storm, and there is a family history connection [to it] because the captain's name was Edward Balson. [T]he East India Company obviously blamed him for what took place. But I don't think he had much choice because of the storm.

Now, sand banks are an incredible interest at the moment because of renewable energy. They form a site that is ready-made [on which] to put wind farms. And one of the reasons for that is because they are a hazard to navigation, unsurprisingly. Because we know that ships shouldn't really be there. They won't be able to get into the very shallow tops of the sand banks, so these wind generators are relatively safe from being collided [into] by a large ship. That's one of the reasons. The other reason is [that] the water is fairly shallow and the engineering is fairly straightforward, so it's easy enough to put a pile in, [and] to put the wind farm on. So there's a lot of interest in that, a lot of studies have been done for wind energy.

Another reason we should be interested is that [sand banks] form a natural coastal defence. [W]here they are found offshore, incoming waves will be reduced, the energy will be reduced hitting the coast. And that might have a significant effect on coastal defence. So I suppose it's a bit ironic that I show a picture of a house which is not being defended at Happisburgh. But, of course, the people of Happisburgh, the Action Group there, [have] accused all sorts of things of being responsible. But, of course, there is a major bank just offshore, called Happisburgh Bank, which actually has been protecting them for quite a while.

They are important habitats, under the EU Habitats Directive. Now, in fact, [sand banks] are fairly barren in terms of biodiversity because of the mobility of the sand. But they are very important habitats for sand eels, [which are food for] birds. [Also,] where the banks are exposed at low water they form important areas for seals. Obviously there are some other fauna, but those are the main issues in terms of designations as special areas of conservation.

Sand banks can also be [sources] of construction aggregate. They represent a huge mass of sand, all in one place, quite easy to get at. So [they are] attractive for dredging for aggregate and also for material for beach recharge. The Norfolk Banks haven't really been subject to much of this at the present time, but some of the [sand banks] in the Bristol Channel have.

[Conflicts of interest]

[F]rom these different [reasons] for interest [in sand banks], you might realise that some [reasons] are not entirely compatible. So if you are going to exploit something for construction aggregate, that's sort of incompatible with its habitat designation. And that's another reason for the interest, in that we need to know more about the natural process, so that we can advise on the conflicting interests for use of sand banks.

[T]he area that I'm going to focus on now is the Northwest European Shelf, and you can probably make out that it's pretty shallow [presumably pointing out this area on a PP slide]. [T]he area that we're looking at is down here — very shallow indeed, only 20m to 35m deep. If I zoom in a little on that you can see how extremely flat it is and it's quite shallow [referring to his PP slide].

[The Norfolk Banks and sea-level rise]

These are the banks we are going to be talking about. They have been picked out in the blue outline here. As you'll notice, the Norfolk Banks out here are very straight — elongate, perhaps 50km or 60km long. When you come in near shore they tend to be a bit more sigmoidal, a bit more Z-shaped; and that partly reflects their mobility. So these banks in here are very mobile. As you know, Scroby Sands Wind Farm is just in there [pointing to PP slide]. These are mobile features, whereas we believe that these features are less mobile [pointed out on PP slide].

[N]ow, I said this area was flat and of course one of the metaphors for flatness is a billiard table. [T]o give you some idea, the specification for a billiard table — flatness — is 1 in 5,000. It should not exceed a slope of more than 1 in 5,000. Well, the area of the Southern North Sea that the Norfolk Banks sit on has a gradient of 1 in 8,000 to 1 in 15,000. So if you like, [the Norfolk Banks are] flatter than a billiard table. [They] do have lumps on [them], but we are talking about the overall gradient.

Now that means that when sea level rises — after the last glacial period, when sea levels were perhaps 120m [lower than today], the sea level started to rise again as a result of melting ice.

It rose very quickly at first. You can see here from 10,000 years ago, you can see it down here at 50 or more, rising very, very steeply [presumably a chart or graph of sea level over time on a PP slide]. Something like 2cm, perhaps a bit more, per year. So it's a very steep sea-level rise here. To give you an idea, at the moment people plan for sea-level rises of *c.* 2mm to 4mm per year. And here [pointing out some time period on the PP slide] we've got 2cm per year. So that's really very rapid.

[T]he effect of [this rise], when you have a very low, flat area is, of course, [that] the transgression occurs fast, very rapidly. So with a small increase of sea level, we get a big change in where the coastline is. So if you like, with a [1 in] 15,000 gradient, a sea-level rise of 1m would mean a 300m displacement of the coastline.

One of the things I think is interesting about that is that there is a lot of interest in the area now around the Norfolk Banks for archaeology. It's quite likely, because that was the last place that was connected to the continent, that there were people migrating, or going about their business, on that flat plain. Now [if there is] the translation of the shoreline of 300m in a year — you'd have thought they'd notice that. You know, you'd have thought that even then, they'd notice that something was changing. That suddenly you'd got 300m lost this year. So it's a big change from a human perspective as well.

So just to look at a little animation of that [short PP video shown]. This is the situation 8,000 years ago, or 8,000 BP. For those of you in the know, BP is not quite the same as calendar years, so this would be probably 8,500 calendar years, but this [8,000] is the radiocarbon years. So *c*. 8,000 BP we can see that we [the British Isles] [were] still connected to the Continent. Obviously there was no connection across the Dover Strait. A lot of people think that there was, but there wasn't in the early Holocene. So people could have migrated across this land bridge. *[These last three sentences appear to contradict each other, but I think what Dr Balson was referring to is that at* c. *8,000 BP there was a land bridge elsewhere than across the present Dover Strait. — Ed.]*

We move on just 1,000 years and again because of that flatness the sea transgresses across that really quickly. And we can see that it's breached and we have this area that we're going to be talking about now attached just to Britain.

[B]y 6,000 BP it's [sea-level rise] almost all over. The sea has risen and apart from a few bits and pieces here and there, we're looking at a geography that's very much like today. So that's when all the big change took place.

[Well, Swarte and Ower banks]

[R]eturning now just to introduce the Norfolk Banks. The Norfolk Banks are these very large sand banks, just off the north-east Norfolk coast. And again, I'll remind you, these are 50–60km long. [If we] take a section from south-west to north-east, we can see a couple of things here. We can see that generally [the banks are] steeper on this face and less steep on that face [presumably from SW to NE pointed out on a PP slide]. Now this is a highly exaggerated section, so that slope there is about 7˚, so they don't really look exactly like that. One of the things that I want you to note, is that come down to about –35 here, they are pretty much all sitting on a plane that is *c.* –35.

Now, a few years ago we did some seismic [research] across these banks and we got some good quality seismic [records]; they were very revealing about what was going on inside the bank. This is a section of Well Bank and as you can see, there's that steep side, which is angled towards the north-east [pointed out on the PP seismic slide]. And within the bank, can you see all these dipping reflectors, here? Now what that means is that we are seeing something a bit like a massive dune that is migrating from south-west to north-east and laying down layers on the front side. You can see some little sand waves there just at the bottom. And so the whole bed form is moving north-eastward.

Another bank, this is one [farther] out still, called Swarte Bank. And again you can see these typical dipping reflectors going all the way through the whole body. And notice how flat that base is: very, very flat. (Ignore this [pointing out something at the lower part of the PP seismic slide]; this is something called a seabed multiple, which is an artefact in the record. It's basically a reflection of the seabed and you see it going on there — there's three multiples there.) So we're only interested in this up here. That's the base of the sand bank — very, very flat; and you can see these dipping reflectors.

Going back to Well Bank again, you will notice this little channel deposit underneath the bank there [pointed out on the PP slide]. [T]hat's a typical feature of this area, that there is pre-existing topography that the banks have just migrated across.

And here's Ower Bank — you can see another little channel there. If we zoom in on that we can see [that] this is *c.* 15m scale, so this is *c.* 4m or 5m thick. And in these channels we find peats, which are freshwater peats, formed in the Mesolithic period — *c.* 10,000 to 11,000 years ago. There [have] been archaeological remains found in these peats, including a spearhead that was dragged up by a fishing trawler in the [19]20s. And so there's a great deal of interest in what was going on in this area before the sea came in.

Then, on top, these channels are usually infilled with intertidal deposits — so muds with shells, representing a tidal flat. So again, [such] tidal flat[s] would have been extensive because of the gradient and probably very short-lived, because the rapidity of the sea-level rise means that that intertidal period could not have lasted very long at any one location — the sea was rising that quickly.

This is another section of Well Bank. Well Bank's quite an interesting bank, a very large bank. What I want you to notice here are these little areas. There [are] three of them: one, two, three [pointed out on a PP seismic slide of the Norfolk Banks]. And if we look in detail you can see the dipping reflectors here and you can see a reflector there, and it looks like [they represent] a little unconformity, a discontinuity within the bank. [Perhaps they] represent a time when the bank stopped and then there was a bit of erosion, or perhaps it changed its behaviour a little and then moved forward again. There were three of those [features] in the Well Bank, [and they show] that [the sand dune-like] progression may not have been continuous — it may have had interruptions. But generally, [the progression] was unidirectional — it just kept going north-eastward.

In the [19]60s one of the first serious scientific studies of sand banks, and of the Norfolk Banks in particular, was done by Houbolt, a Dutchman, and he was the first to take cores. [T]hese [a PP slide thereof] are six cores. [J]ust concentrate on these two here. [Houbolt] noticed these bands, which are thin bands of mud within the bank sediments themselves.

This [another PP slide] is a BGS core taken 30 years later and it's very similar. It's much longer, this is nearly 4m [to] 4.5m long, whereas Houbolt's were only 75cm [long]. But again look here, you can see these little thin bands of mud. So what does that

mean in terms of the way the bank was moving? Does it mean that there were periods of quiescent tidal currents and then deposition from suspension? [Houbolt] believed that the Norfolk Banks sit within a very muddy area of the North Sea, sometimes called the North Sea Plume. This is a satellite picture [another PP slide]. Obviously the banks we are talking about are in here and this cloudiness you can see is mud in the water of the North Sea. Some of this mud is coming up from the south and a lot of it is coming from over here (which unfortunately is not in this image) from Holderness — the cliff erosion in Holderness. That mud is going into the water column, suspended and drifting around here and then going up here.

(I thought this was a nice image. The scratches, what look like scratches on that, do you know what those are? Those are contrails from passenger aircraft. It's very spectacular isn't it?)

[Internal structure]

So, just to summarise the general setting. We've got a very flat plateau, *c.* 35m below present sea level. It was transgressed very, very rapidly *c.* 8,500 to 7,000 BP and there were extensive tidal flats overlying these Mesolithic peats.

Now, what can we tell from the internal structure about how the sand bank moved or how it progressed? If we look at this bank again [apparently returning to the PP seismic slide], we can see these dipping reflectors. If there's a dipping reflector there, which there is, that must represent the toe of the bank when the crest of the bank was over here. You've got the bank here and it moves forward, so each of these is a record of that face there as it translates. [T]hat means that we know that this bank has moved at least from there to there. And in the case of Well Bank, that can be up to 5km. So if you like, it puts a limit on the migration. We know it's at least 5km, [and] it could be more. And we know, because all these reflectors are exactly the same, that it's a progression north-eastward. There might be some stops but it does-not seem to have reversed. There doesn't seem to have been erosion followed by other depositions. It seems to be a pretty much simple unidirectional migration.

So on these banks we've got flat, erosional bases. We've got an internal structure showing consistent north-eastward migration. We've got Well Bank, at least moving 5km, maybe more. And if we think that sea level means that up until about 5,000 years ago there wasn't even enough water there to have a bank, so that puts our other constraint on how long they have been evolving. Well, if they were there 5,000 years ago and they've moved 5km, that's a migration rate of 1m per year. As I've said a huge caveat. That's assuming that it was consistent over the whole time period, over 5,000 years. It might have been faster at certain times, it might have been slower, because there is evidence for some episodes, some episodic migration.

[W]ith all the technology we have now we can look at the 3D shape and form of these sand banks and we can produce things like isopachs. [H]ere's an isopach of Well Bank [a new PP slide] and you can see that the crest is obviously on this side, it's asymmetric. That's the north-east up here. You can see that we're getting up to 35m thick, so it's very thick. And it means that from this [data], we can calculate how much sand there is in Well Bank.

[Amounts and sources of sand]

The next table I'm going to show you is a calculation [of] how much sand are we really talking about? [PP slide of table shown] [I]t's divided into three areas of banks, which we've named here the Inner Great Yarmouth Banks (these are these very mobile, sigmoidal-shaped banks), the much bigger Norfolk Banks and some banks over here called the Dudgeon Dowsing Shoals.

But for completeness we want to know how much is in this sedimentary system. And these are the volumes of sand: the Norfolk Banks — 7.3 *billion* cubic metres; the Inner Great Yarmouth Banks, because they are in shallower water, they are not as thick, have much less volume; and the Dudgeon Dowsing Shoals are also in fairly shallow water and again the volumes are commensurate with that. So we've got a total here of 10 *billion* cubic metres, which is actually 10 cubic kilometres. So in terms of the North Sea sedimentary system, this is a massive sink for sand. It's where sand goes to die! It's absolutely massive.

So where could that sand come from? Well, there [are] three obvious places:

1. It could come from rivers. [T]hose of you who know the east coast of England know that there aren't really very many big rivers in the east of England, apart from the Humber and the Thames. In between there are a number of small rivers — not very big [ones].
2. There's coastal erosion. Again anybody who knows this area of the coast knows that coastal erosion is a huge issue.
3. And, of course, the thing we don't see — sea-floor erosion. And it's also the one thing that it's hard to get numbers on, because we can't see it and it's hard to measure.

So if we look at the inputs from cliff erosion, [there are] three main areas:

- Holderness, where cliffs are eroding 2–3m a year, [cliffs] up to 25m, 30m high.
- North-east Norfolk itself, like Happisburgh much to the residents' annoyance, 1m a year [or] perhaps a bit more.
- And there's also a small amount [moving north] from Suffolk. Now, some people say [that] Suffolk is eroding a lot. [I]t is, but unfortunately a lot of that material goes south into the Thames estuary, so that's not included — only the parts of Suffolk where the sediment [is] going north.

[Looking] at these sources:

- Holderness (this is in millions of cubic metres a year [the values on the PP slide being shown]) [is] by far the biggest source, but it's mostly mud [rather than] sand. So we've only got just over a million cubic metres a year coming from Holderness.
- *c.* 0.4 [we are to assume 'million cubic metres] from north-east Norfolk, and
- 0.03 from Suffolk,
- [but] almost nothing from the rivers that is sand; because what little that comes out of the rivers is mostly mud.

[S]o we've got the sand input from coast erosion of 1.63 × 106 cubic metres a year. And the volume in the Norfolk Banks [is] this 10 billion [cubic metres] figure. And when we divide one by the other we [find] that the Norfolk Banks would require 6,000 years of supply at that rate. So you think Bingo! That's it solved — it's almost, as near as makes no difference, the right number.

But we're not sure that any of the Holderness material does go to the Norfolk Banks. We know that there are other sinks of sand [that] are closer to Holderness. One is the mouth of the Humber.

There's a huge amount of sand at the mouth of the Humber. And, of course, [there is] The Wash. A lot of sand travels down the Lincolnshire coast and goes into The Wash.

So, what [time period would we get] if we disregard the amount coming from Holderness? Well, then it would take 23,000 years. And we know we don't have 23,000 years, we only have at the most 6[,000]. Because that's the only amount of time that the water was deep enough to generate sand banks.

So [what are] the caveats we've just [heard]? We're assuming that this present-day rate of input is typical over the entire period. We're also assuming it's accurate, which is notoriously not true. People come up with all sorts of numbers for how much sand, or how much material, is derived from erosion. There can be orders of magnitude difference, so that is a real problem. Also, not all this sand — and I'm just talking about sand — is the right grain size. These sand banks are very well sorted, fine to medium sand. [N]ot all of the sand that comes from Holderness is fine to medium; you'd expect the coarser sand perhaps to go [to one place] and the finer sand to go somewhere else. So even if we took all that Holderness material, how much of it could potentially go into the banks? It's not very much. And we're also assuming that all the offshore sand is in the Norfolk Banks, [which] it isn't. There are lots of other bodies of sand, which aren't banks, such as sand waves, sheet sands and infills into hollows, which would change those numbers — the actual amount of sand.

So what [are] other sources? It sounds like we're short of quite a lot of sand. Well, just to remind you, this is *c.* 18,000 years BP. We're in the middle of an ice age. This is the late glacial maximum and we have a huge ice sheet over Scotland [pointed out on a PP map or graph slide]. And this reconstruction shows this tongue of ice coming down the North Sea, terminating in Norfolk. [The] figure [of] 18,000 is a 1995 reference. People now doubt that 18,000 years would be correct, because although this might be the date for the late glacial maximum, when the ice was thickest over Scotland, this tongue might be later. It might have gone [on] as late as say 15,000 BP. [Although it is] not really important from the context of what I'm trying to tell you, but this is a late glacial development, this surge of ice down the east coast.

So if we now look at where the banks are, relative to where that ice front might be — this is a BGS geological map [and] this speckl[ed] area here is lodgement till from that ice sheet — we know, if it's a lodgement till, that the ice went at least that far because it had to have been formed under the ice. So it's possible that the ice front went farther than that line. And look where the banks are, they are right in this area. So immediately you start thinking about glacial outwash, [about] cover sands — all the sort of depositional bodies that you might get at an ice front. So when the ice was here, there would have been an awful lot of sand about — sand and gravel and other materials. And so that must have formed part of the source for these huge bed[ding] forms. And of course we can't easily get a figure for that because it's all been moved, inconveniently.

[Source of Norfolk Banks sand]

[G]oing back to this question about the sources: Where did the sand come from to make the Norfolk Banks? We've got rivers, which we've hopefully agreed are insignificant and probably were insignificant for the entire period we're talking about. We didn't have big rivers that have suddenly gone. We think the rivers over the last 6,000–7,000 years have not been very significant.

Coastal erosion is the only significant source [of sand] today, but that may not be the whole story. And sea-floor erosion in the mid-Holocene was probably one of the key sources.

[T]hat would mean, of course, that these are slightly fixed amounts of sand. They're not renewable in the sense that we're not going to get a lot more sand coming from coast[al] erosion, especially with the defences being put up, reducing [the amount of erosion], certainly in Norfolk. [T]he input has been reduced by human interference.

[Models]

OK, let's look at these models then — these four models from Houbolt [19]68 through to Huthnance [19]82 [presumably another sand bank researcher, not heretofore mentioned by name]. Houbolt's model is based on the work that he did in the 1960s and it says that these banks are really like huge dunes. They migrate, they have an internal structure like a dune and they are maintained a bit like a dune.

Caston [another researcher] [says] that these sigmoidal banks that we see in the Norfolk Banks sort of bud and break off each other, and make more banks — almost like cell division.

Swift [another sand bank modeller], on the other hand, mostly looking at areas off the east coast of America, came up with [the] idea that as a coastline retreats, it leaves banks behind; [that] they are, if you like, spalled off a migrating coastline, particularly where there are headlands.

And then Huthnance in [19]82, [who took] a much more mathematical approach, said that there has to be a perturbation to the flow before you can get a bank. So you have to have, if you like, a core, or something that would disrupt the flow enough to get the deposition. So he said there must be an origin from a bedform perturbation.

[A]ll of [these models] are being applied to the Norfolk Banks. So this [another PP slide] is Houbolt's model and you can see that this looks pretty much like what we saw in the seismic [record]. We've got oblique bedding with a steep face and a shallow face, sand waves migrating over the surface and the sand waves are largely responsible for the internal reflectors. So that, in a way, seems to fit.

Caston's model [another PP slide] shows a single bank, and because of the opposing tidal currents you get a little deviation, a little kink, and that kink quickly grows and you end up with three banks. So you start with one, [and] you end up with three. [It is] a little bit difficult to see how you can do that, unless you've got a lot more sand coming in. Otherwise these would be three smaller banks from the one bigger one at the start, but that was [Caston's] model.

[On] Swift's model [another PP slide] — this is Nantucket Island on the east coast of the United States — you can see these sand ridges, which, if you like, he imagines is the retreat path of the island.

Huthnance's model is a bit more problematic [another PP slide]. Not because it's wrong, but because we haven't got the evidence. [T]his bank, because it's got these internal dipping reflectors all the way through, must have migrated at least one wavelength away from whatever perturbation started it. So we can't tell what caused the bank to start. That's an important bit of evidence from the internal structure.

[Norfolk Banks — classic or unique?]

I want to just say a few words now, about some other banks in the North Sea [that] shed some light on whether the Norfolk Banks are classic or unique.

The Flemish Banks are extremely well studied [pointing them out on another PP slide]. One of the reasons they're well studied is because of the shipping routes into Rotterdam and Zeebrugge; and also because the Belgians have a fairly small continental shelf and they are very keen on sand and gravel aggregate resources. So they have been doing a lot of work to see if they could dredge up some of these sand banks without affecting their coastline.

So I'll say a few words about that area and also this little area up here: these bank ridges off the Dogger Bank.

Now in Stride's classification, these are what are known as 'moribund'. They were formed perhaps thousands of years before the Norfolk Banks, when the Dogger Bank was an island and before the sea even got into this area. And these bank ridges, in the same way as the Norfolk Banks, are parallel to the coastline — that [is], the coastline at some earlier point and these are parallel to the Dogger Bank.

Now, this [another PP slide] is just partly to show you that nowadays multibeam [bathymetry] gives you some fantastic images of these sand banks. This is Kwinte Bank, one of the Belgian banks, [which has] been studied in great detail. And you can see the sand waves here, transverse to the flow, quite a complex pattern of sand waves. Unfortunately, I haven't got a good section to show you but the internal structure of Kwinte Bank is very complicated, it's very complex. It seems to show changes of direction; it seems to show periods of cessation and then regrowth. The sand waves show migration in various directions, sometimes going one way, sometimes going back the other way.

So the Belgian Banks generally seem to be much more complex than the Norfolk Banks. They don't seem to have just this simple unidirectional migration.

We come to one of the east bank ridges [another PP slide]. Unfortunately, none of them have names, so this is just one of the east bank ridges. [Here] we see something completely different. As you notice, a very smooth profile. This is in perhaps 90m of water now. We don't know what water depth it was formed in, or initially formed in. But [we can see that it is] quite clear [that] there is hardly any structure in the top part, and the lower part seems to have these horizontal reflectors, which are truncated either side. [These structures are] nothing like the Norfolk Banks.

So why is that? If they formed on a coastline off the Dogger Island, a bit like the Norfolk Banks formed off north-east Norfolk. [So] why don't they look in any way similar?

Well, one of the reasons is that the grain size of those east bank ridges is very fine sand, whereas the Norfolk Banks are fine to medium sand, so quite a bit coarser. Now if we look at this plot [another PP slide] — this is from an Open University textbook — we can see that if you have grain sizes less than about 150 microns (this is current speed up the side, grain size on this side) [we must assume that the graph shown displayed grain size and transport speeds] [?that it would be transported and distributed differently].

Well, let me start first with the Norfolk Banks, we've got a grain size round about here [indicated on the PP OU plot slide], and as currents get more rapid, we go through a ripple field, mega-ripples or sand waves and then to sheet deposition. So our sand waves form here [on the plot slide] — for that grain size they form here, between *c.* 0.6m s^{-1} and 1m s^{-1}[, respectively]. We get sand waves.

If we look at the grain size on the east bank ridges, however, we get down [to] this end of the scale, [where it goes] from ripples to sheets. There are no sand waves. We can't form sand waves in very fine sand. So once you can't form a sand wave you can't get [the] bedding [that is seen in the Norfolk Banks]. You can't get that same kind of maintenance of a bank [that is seen in the Norfolk Banks].

So grain size turns out to be critical to the structure and the behaviour of the bank.

[Conclusion]

[What] conclusions [can we draw] from what [we've] seen? The Norfolk Banks are an important component of the North Sea sediment transport system. As I've said they are this massive sink, 10 billion m^3.

The banks first formed *c.* 5,000 years ago, although the nearshore banks must be more recent. And the reason they must be more recent is because the sea took longer to get to that location. So, for instance, if you are farther offshore, the water would deepen enough to form a sand bank, while perhaps somewhere else was still dry land. So we know that as we go closer in [to the coast], the time available must diminish.

[The Norfolk Banks] contain 10 billion m^3 of sand derived from both glaciogenic sources [that] were left behind by the retreating ice, and [from present-day] coastal erosion. And they appear to have migrated offshore over time.

So one of the [conclusions that] we can derive from this [information] is that the surface geomorphology alone is not enough to interpret evolution. We can't just go looking at charts and say, "It's moved 100m in 100 years". Over a long period of time, that might not be typical.

[T]he only way to really know what has happened over a geological timescale is to look at the internal structure [of the sand bank]. Geomorphological changes over the decadal to century timescales are problematic because we don't have a long enough snapshot. Are those changes related to evolution? Or are they just noise in what is going on?

And finally, there is no single evolutionary model that we can take and just [apply to] a different group of sand banks. So we couldn't, for instance, take the model for the Norfolk Banks and apply it to the eastern US[A] or [to] China, or [to] anywhere else. We have to look at a much more complex situation than perhaps we have given it credit for in the past.

Thank you.

Did the sea taste salty to the dinosaurs?

Dr Christopher Pearce

(Research Fellow at the University of Southampton, National Oceanography Centre, European Way, Southampton, SO13 3ZH)

Abstract

The salinity of seawater is arguably the most important control on physical, chemical and biological processes that occur in marine environments. It also plays a major role in the regulation of Earth's climate by affecting ocean circulation and the distribution of heat.

The salt content of the oceans reflects the relative abundance of ionic species, which is determined by the magnitude of marine input and output fluxes over geological timescales. Measurement of fluid inclusions preserved in ancient evaporite deposits reveal that the concentrations of principal ions such as magnesium, calcium and sulphate have varied cyclically over the last 500Myr, contradicting the long-standing assumption that the processes that maintain seawater salinity are buffered against such changes. Although the causes of this secular variability remain heavily debated, proposed mechanisms include changes in the rate of mid-ocean ridge spreading and shift in continental weathering rates as a consequence of global climate change.

This lecture presented the evidence for the long-term variations in the major ion composition of seawater and discussed the results of on-going research aimed at resolving the processes responsible for these changes. It also focused on the implications of these reconstructions on the temperature, pH and carbonate saturation of past seawater, which represent some of the principal controls on the long-term evolution of calcifying marine organisms and atmospheric CO_2 concentrations.

[OUGS Canterbury Symposium: Marine Geotales; original transcription by Jim Camp from the seminar recording; writtten up by Dr Pearce]

Did the sea taste salty to dinosaurs? It is easy to say that it does today, therefore it must have been like that when T-Rex roamed the planet. However, you do not need to be an academic to ask yourself where the salt in the sea comes from and whether it has always been the same: One of the earliest chemistry lessons I can remember from school was watching a pan of seawater evaporate, leaving behind its salty residue and wondering where on earth all of those crystals came from. This question of what makes up the salt content of the oceans, and how it has varied through time, is just one of the topics that I am investigating at the University of Southampton, and is what I will be discussing in the rest of this seminar.

What is the salt content of seawater?

Let us begin by defining what we actually mean by the 'salt content' of the seawater (Fig. 1). More commonly termed salinity, this concept basically refers to anything dissolved in the ocean that is not water. When defined using 1kg of seawater, these solutes and ions weigh *c*. 35g, giving us an average seawater salinity of 3.5% [today]. Although we have known about the presence of these extra components in seawater for a long time (the early Greeks referred to the saltiness of seawater as the sweat of the Earth), the concept of salinity was not formally introduced until 1865 by the Danish chemist Johann Forchhammer. Forchammer was the first person to measure the different constituents of the oceans, demonstrating that in addition to water molecules, seawater contains chlorine, sulphate, magnesium and calcium, as well as many other ions. He was also the first to determine the concentration of sodium in the oceans. However, Forchammer's limelight was subsequently stolen by William Dittmar, whose analysis of 77 samples collected from various depths in different oceans during the *HMS Challenger* expedition of 1873–6 gave us the first accurate definition of salinity at 3.5%. Shortly after this, in 1901, Martin Knudsen defined salinity as a function of the chlorine content, but it was not until 1969 — almost a full century after Forchhammer's initial investigations — that the International Oceanography Committee (IOC) finally decided on an empirical definition of salinity as: S(‰) = 1.80655Cl(‰).

Figure 1 Salt crystals on the Dead Sea shoreline (Internet source: reproduced for educational purposes only).

Despite taking almost a century to get to this point, the IOC quickly changed its mind, and just less than a decade later switched to using the practical salinity scale, which is the reference scale most commonly used today. This scale differs to the older methods that defined salinity as a function of chlorinity in that practical salinity is measured using the electrical conductivity of seawater relative to a potassium chloride standard solution — an obvious benefit when using electrical salinometers. Our attempts to characterise seawater salinity have not quite stopped there, however, and just a few years ago (in 2008) Millero and co-workers published the 'Reference-Composition Salinity Scale'. I am sure there will be further developments on this as research moves forward, but the key feature that all of these scales have in common is that they demonstrate that the salt content of the oceans does not just depend on the major elements of sodium and chlorine; it is a function of many different elements, some of which are only present in tiny amounts (Table 1, *overleaf*). It is these other components of seawater salinity, such as magnesium, calcium, potassium and strontium, on which my research focuses.

© OUGS ISSN 2058-5209

Table 1 The composition of seawater (from Millero *et al.* 2008)

Constituent	Concentration (mol/kg)	Fraction of sea salt (%)
Chloride, Cl^-	0.545870	55.034
Sodium, Na^+	0.468967	30.660
Sulphate, SO_4^{2-}	0.028235	7.713
Magnesium, Mg^{2+}	0.052817	3.651
Calcium, Ca^{2+}	0.010282	1.172
Potassium, K^+	0.010208	1.135
Bicarbonate, HCO_3^-	0.001718	0.298
Bromide, Br^-	0.000842	0.191
Borid acid, $B(OH)_3$	0.000314	0.055
Carbonate, CO_3^{2-}	0.002390	0.041
Strontium, Sr^{2+}	0.000091	0.023
Borate, $B(OH)_4^-$	0.000101	0.023
Fluoride, F^-	0.000068	0.004
Dissolved CO_2	0.000010	0.001
Hydroxide, OH^-	0.000008	0.000

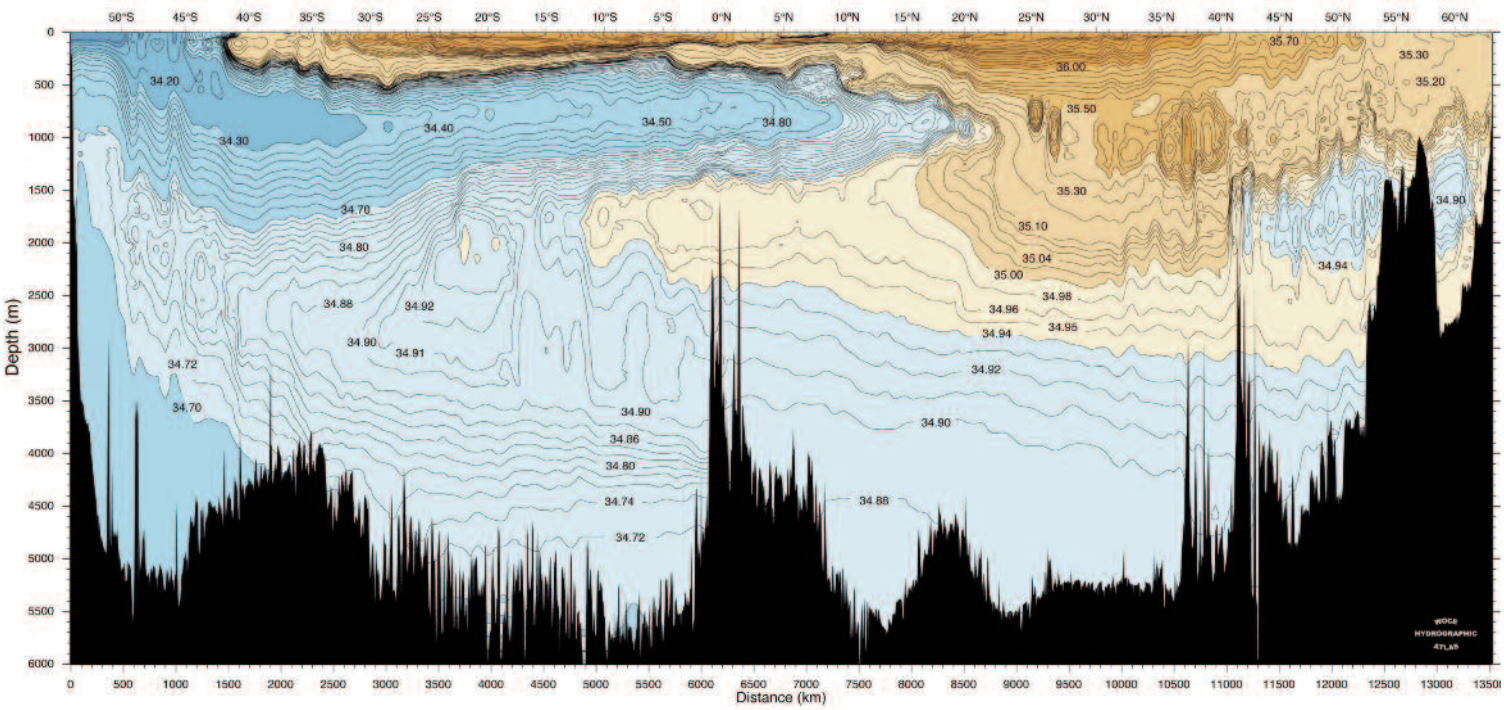
Is the salt content of the oceans always the same?

Now that we have defined what we mean by the salt content of the oceans, we can start to consider if, and how, it might have varied through time. Anyone who has studied the OU's Oceanography module S330 should (hopefully!) be able to tell you that the salinity of the modern oceans is not always the same; it varies considerably with water depth and location. These variations are primarily driven by processes such as evaporation, the formation of sea ice and freshwater input from rivers and melting glaciers, and are relatively straightforward to quantify. For example, depth transects through the Atlantic show particularly pronounced variations in surface waters (Fig. 2). Monitoring and understanding the processes that affect the salinity of the oceans is of major importance, as this is a key factor driving thermohaline circulation, which as anyone who has seen the film *The Day After Tomorrow* will already be aware, helps distribute global heat and regulate Earth's climate. In 2011 NASA launched the satellite *Aquarius*, which has enabled us to measure annual variations in the salinity of the surface oceans for the first time using microwave emissivity. Using these measurements NASA researchers are able to produce an annual integrated map that shows how the salinity of the surface ocean is changing through time.

A crucial aspect of these variations in seawater salinity is that although the total amount of salt in the oceans can change both spatially and temporally, the relative proportion of the various ions that make up that salt do not change; they remain the same no matter where you go. This facet of seawater salinity has been proven time and time again in the modern oceans, and was actually first recognised in 1819 by Alexander Marcet, who noted, "All the specimens of seawater [that] I have examined, however different in their strength, contain the same ingredients all over the world, these being very nearly the same proportions to each other, so that they differ only as to the total amount of their saline contents". Today this concept is known as Marcet's theory of proportionality, and led many researchers to believe that the composition of seawater was fixed soon after the first oceans were formed early in Earth's history.

That belief was shattered in 2001 when Lowenstein and coworkers published an article in *Science* entitled 'Oscillations in Phanerozoic seawater chemistry: evidence from fluid inclusions'. In this paper Lowenstein *et al.* chemically analysed tiny fluid inclusions (little bubbles of seawater) trapped within ancient evaporate deposits, and used their results to estimate what the composition of seawater would have been at the time that the evaporate deposits formed. Remarkably, their results showed that, instead of remaining constant through time, the ratio of two of the most abundant ions in seawater — magnesium and calcium — has increased by a factor of 5× over the last *c.* 100 million years. Furthermore, they showed that there appeared to be clear cyclic variations in the relative proportion of these ions over the

Figure 2 Salinity variations with depth through the Atlantic (Internet source: reproduced for educational purposes only).



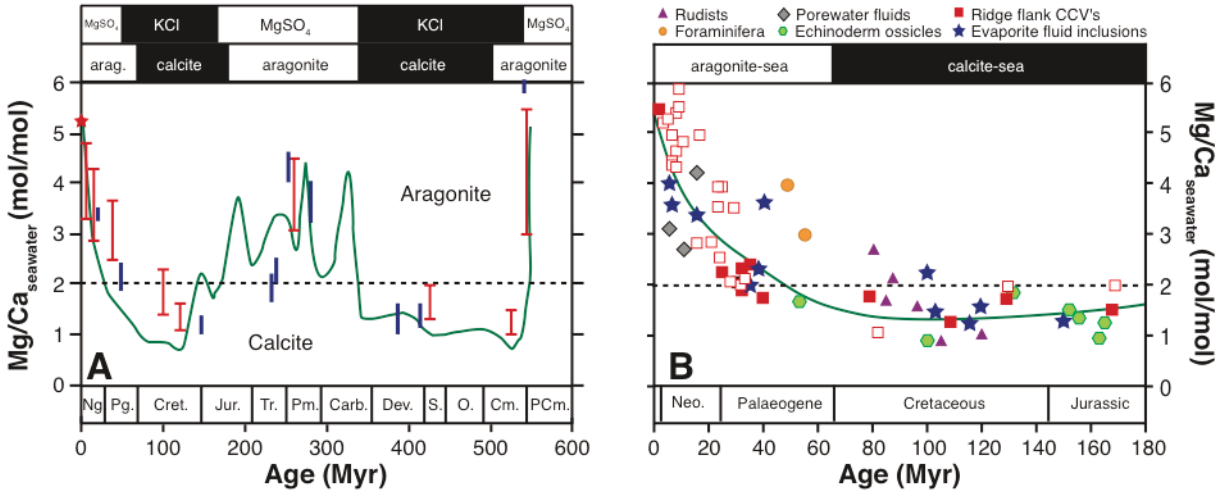


Figure 3 A — Mg/Ca ratios 600Ma; B — Mg/Ca ratios 180Ma (redrawn using data from Coggon et al. *2010; Ligi* et al. *2013; Lowenstein* et al. *2001, and references therein).*

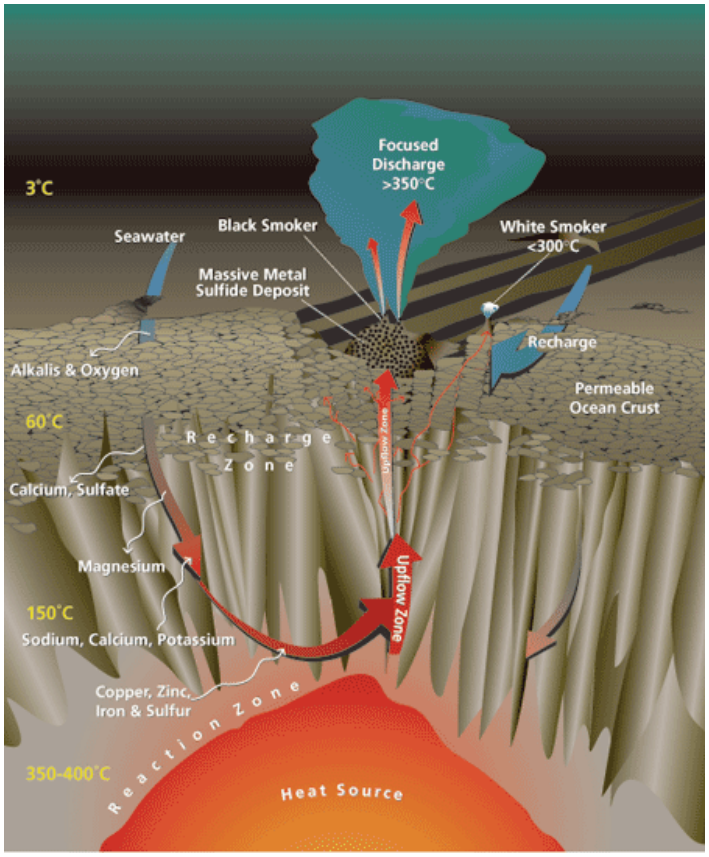
Phanerozoic Era, and that these vatiations were matched by equivalent changes in the nature of the dominant salts (Hardie 1996) and carbonate structures (Sandberg 1983) being precipitated (Fig. 3A). One of the problems with this early dataset was its low resolution, as it was limited by the availability of suitable evaporate deposits from which to extract chemical data; their entire 600-million-year reconstruction was based on fewer than 20 samples. In order to try and understand the mechanisms responsible for these changes scientists have since been focussing on the variations in seawater chemistry over last 180 million years (the age of the oldest known ocean crust). These subsequent studies have used rudists, corals, foraminifera, echinoderm ossicles, pore water fluids and calcium carbonate veins (CCVs) to estimate changes in seawater Mg/Ca ratios over this period (e.g. Coggon *et al.* 2010; Ligi *et al.* 2013; Fig. 3B). These data pretty much confirm the original results of Lowenstein *et al.*, and indicate that if you were to go back 100 million years or so, when dinosaurs were going for a dip in the oceans, the Mg/Ca ratio of seawater would have been a lot lower than it is today. Most of this change has occurred during the last 60 million years, raising the question of what mechanisms have varied over this interval in order to drive such significant changes in the composition of sea salt.

What processes may have caused the composition of the oceans to change through time?

Like any other element in the ocean, the abundance of the major salt-forming ions in seawater is dependant on the relative balance between the input and output fluxes. There are many processes that can act as either a source or sink of material in the oceans, including volcanic emissions, continental riverine discharge, hydrothermal vent activity, sediment formation and, of course, biological processes. Volcanic activity plays a major role in the transport of volatile negative ions such as chlorine, bromine and fluorine. Intensive volcanic activity and magmatic degassing during Earth's early history meant that these ions were quickly released as gases from the mantle. Once present in the Earth's atmosphere, they were dissolved into water and (ultimately) into the early oceans. Although volcanic activity still releases these ions, this more or less matches the quantity lost at subduction zones. Thus, most of these negative ions are recycled through ocean spray back into the oceans. As there is no evidence that the chlorine content of the oceans has changed significantly over the last 600 million years, we can most likely discount volcanic activity as a source of variation in the other major marine elements.

Hydrothermal fluids play an equally important role in controlling the composition of seawater, with black smoker vent fields acting both as sources of and sinks for marine ions (Fig. 4). However, we now know that the nature of the reactions occurring within hydrothermal systems is very varied and depends a lot on the temperature of the reaction that is taking place. For example, magnesium is rapidly removed from seawater during high temperature interaction with the ocean crust, but only partially removed at lower temperature, off axis sites. This contrast led

Figure 4 Element exchange at hydrothermal vents (Internet source: reproduced for educational purposes only).



Hardie (1996) to suggest that changes in the rate of ocean crust production may have been responsible for the shift in seawater Mg/Ca ratios through time, with intervals of rapid crustal formation associated with lower Mg/Ca ratios. This concept was taken forward a step by a group of Italian workers (Ligi *et al*. 2013) who published a paper suggesting that the long-term compositional changes in seawater may reflect differences in the weathering of the ocean crust. Specifically, they hypothesised that interactions between seawater and peridotite play a major role in determining marine chemistry, and that the weathering of these Mg-rich upper mantle rocks is lower when the rate of ocean ridge spreading is faster because seawater is unable to penetrate as far into the crust.

A major problem with both of these theories, however, is that there is no evidence that the rate of mid-ocean ridge spreading has varied significantly over the last 60 million years (the period associated with the rapid increase in Mg/Ca ratios). To account for this discrepancy, Wilkinson and Algeo (1989) suggested that the dolomitisation of carbonates plays a major role in determining the Mg/Ca ratio of seawater (Fig. 5). Dolomite is a calcium-magnesium carbonate that forms during interaction between pure limestone and magnesium-rich fluids, resulting in the removal of magnesium from the fluid phase. Changes in the rate of dolomitisation could therefore have resulted in major changes in seawater chemistry without the need for a shift in mid-ocean ridge spreading. However, this theory also remains contentious, as there is no clear geological evidence for a change in proportion of dolomite production.

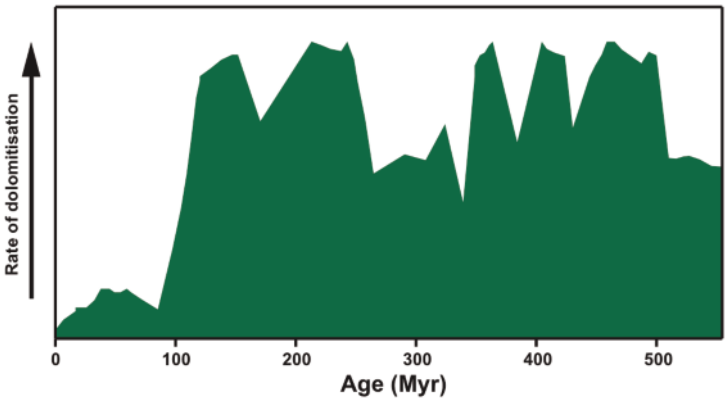


Figure 5 Changes in the rate of dolomitisation through time (redrawn from Wilkinson and Algeo 1989).

Why do we need to constrain these variations in the ionic content of the oceans?

I have highlighted some of the core concepts that have been proposed to suggest why the composition of the major ions in seawater may have changed through time, but I guess the key question is, why do we care? Why is it important to us that we define what the composition of sea salt is today, and what it was like 100 million years ago?

There are several reasons for wanting to know this, aside from the fact that if we want to know about the Earth's major climate processes we need to know the rate of ocean crust spreading and what carbonates are forming in ocean waters. For example, the Mg/Ca ratio in foraminifera (tiny calcifying marine organisms) is one of the key palaeo-thermometer proxies used to reconstruct seawater temperatures back in time. Several of my colleagues at Southampton (O'Brien *et al.*) recently published a study showing that the Mg/Ca ratio of foraminifera agrees quite well with organic proxies for sea-surface temperature reconstruction up to *c.* 2 million years ago, before a clear divergence in the two reconstructions (O'Brien *et al.* 2014). This divergence is thought to be due to changes in the magnesium–calcium ratio of seawater, so if we were able to constrain how the Mg/Ca ratio of seawater has varied, we would be able to get a much better understanding of how temperature varied through time. Another important reason is to understand the causes and consequences of ocean acidification. There is a strong correlation between seawater pH and Mg/Ca ratios, as magnesium and calcium are the dominant ions used in the marine carbonate system. By further exploring this link, and understanding how both pH and Mg/Ca ratios varied in the past, it may be possible to establish what the consequences of modern ocean acidification may be on the long-term composition of seawater.

Summary

Hopefully, I have been able to emphasise in this article that the salinity of saltwater is a crucial feature of our planet, and that it drives many processes, from ocean temperatures to global climate and ocean circulation. Although the total amount of salt present in the oceans may vary from place to place, the relative ratios of the solutes in saltwater remain the same at any given point and at any given time. It is only when we look back into the geological record that we can see that the relative concentrations of the major salt-forming ions have in fact varied as a result of changes in major Earth system processes, such as the rate of mid-ocean ridge spreading or carbonate formation.

Finally, to come back to the question I posed at the start: Yes, the sea definitely did taste salty to the dinosaurs, just perhaps not in the way that we know it now.

References

Coggon, R. M., Teagle, D. A. H., Smith-Duque, C. E., Alt, J. C., and Cooper, M. J. 2010 'Reconstructing past seawater Mg/Ca and Sr/Ca from mid-ocean ridge flank calcium carbonate veins'. *Science* **327**, 1114–17

Hardie, L. A. 1996 'Secular variation in seawater chemistry: an explanation for the coupled secular variation in the mineraologies of marine limstones and potash evaporites over the past 600 m.y.'. *Geology* **24**, 279–83

Ligi, M., Bonatti, E., Cuffaro, M., and Brunelli, D. 2013 'Post-Mesozoic rapid increase of seawater Mg/Ca due to enhanced mantle-seawater interaction'. *Scientific Reports* **3**, 2752. DOI: 10.1038/srep02752

Lowenstein, T. K., Timofeeff, M. N., Brennan, S. T., Hardie, L. A., and Demicco, R. V. 2001 'Oscillations in Phanerozoic seawater chemistry: evidence from fluid inclusions'. *Science* **294**, 1086–8

Millero, F. J., Feistel, R., Wright, D. G., McDougall, T. J. 2008 'The composition of standard seawater and the definition of the reference-composition salinity scale'. *Deep Sea Res* **I 55**, 50–72

O'Brien, C. L., Foster, G. L., Martinez-Boti, M. A., Abell, R., Rae, J. W. B., and Pancost, R. D. 2014 'High sea surface temperatures in tropical warm pools during the Pliocene'. *Nature Geoscience* **7**, 606–11

Sandberg, P. A. 1983 'An oscillating trend in Phanerozoic non-skeletal carbonate mineraology'. *Nature* **305**, 19–22

Wilkinson, B. H., and Algeo, T. J. 1989 'Sedimentary carbonate record of calcium-magnesium cycling'. *Am J Sci* **289**, 1158–94

Bubbles in the Ocean — how a tiny bubble can matter for a planet

Dr Helen Czerski

(Research Fellow, University College London)

Abstract

The fundamental challenge of our research is to link the small-scale physics controlling a single tiny bubble to the gigantic process of how our ocean breathes. Our oceans and atmosphere are constantly exchanging gases and particles across the ocean surface, and these exchanges affect weather, climate and the chemistry of the ocean. The speed of this process depends on the nature of the sea surface, which is complex and can change very rapidly. High winds and swells cause breaking waves and the production of seaspray, and drive turbulence in both the water and the air. The bubbles formed by breaking waves are known to speed up gas exchange and aerosol production, especially when the wind is strong, but the exact details [of how this happens] are still unclear. I discuss how we approach the science and why understanding single bubbles matters, and share results from our recent research cruise in the North Atlantic.

[OUGS Canterbury Symposium: Marine Geotales; original transcription by Maggie Deytrikh from the seminar recording; edited by Dr Czerski and POUGS Editor David M. Jones]

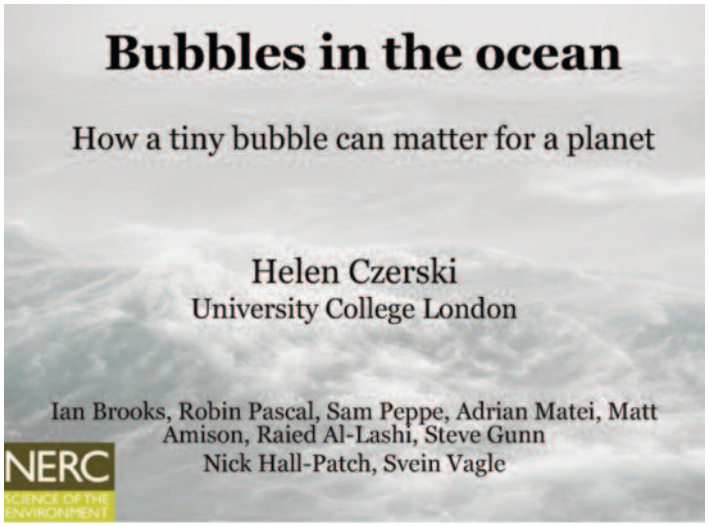
Introduction

Hello, I'm not 'that' sort of physicist, in case anyone was wondering, I hate the *Big Bang Theory*, and the reason I hate it is because a bit of it is a bit too true and I spent years with those people, and oceanographers are much nicer people. But the physics is still very cool, so I do a lot of talking about physics. *[Dr Czerski's amusing comments here refer to the introductory remarks DMJ made for this session of the Symposium — Ed.]*

I am a physicist, and I've been very lucky and done lots of different types of physics. My PhD was in explosives physics, blowing things up, and when I stopped wanting to blow things up, the physics itself took me to ocean bubbles. I became an oceanographer by the back door, going to the Scripps Institution of Oceanography and had a fantastic introduction there. I am going to talk about some of the work I did since and the perspective upon this work. It's all about bubbles and they are cool, the unsung heroes of the physical world — as they are really interesting little things, everyone ignores them; they do all kinds of interesting things and they matter in all kinds of unexpected ways. This [talk] is all about how they matter for the ocean.

I am highlighting the list of names on the title slide (Fig. 1), and I am sure that [what] you will be picking up from all the speakers you hear this weekend is that science, more than ever in our history, is a massive collaborative effort and that whatever you see on these slides, it is never the work of just one person, but a huge team effort. These are some of the people who have been helping with this work currently; there have been lots more in the past. My PhD student, Adrian, is also here [at the Symposium], so if you'd like to talk to him, find him in the break, afterwards.

Figure 1 The scientific team studying ocean bubble physics.


Bubbles in the ocean
How a tiny bubble can matter for a planet
Helen Czerski
University College London
Ian Brooks, Robin Pascal, Sam Peppe, Adrian Matei, Matt Amison, Raied Al-Lashi, Steve Gunn
Nick Hall-Patch, Svein Vagle
NERC

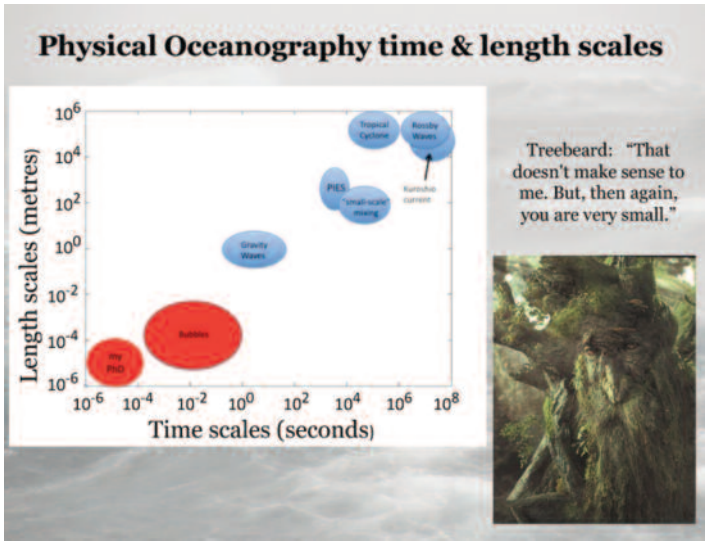

Physical Oceanography time & length scales
Length scales (metres)
Time scales (seconds)
Treebeard: "That doesn't make sense to me. But, then again, you are very small."

Figure 2 Physical oceangraphy log scale of time and length.

Bubbles in the ocean matter

I moved oceanography departments, from Scripps to Rhode Island and this is the first slide that I showed in my first talk at the University of Rhode Island (Fig. 2). I was put into their department of physical oceanography and it took me a couple of months to realise that I didn't really speak the same language as everyone else in the building; and it took me a couple of months to work out why? This is why: When I did my PhD, all the explosives physics was happening in microseconds and very small timescales, too small to see. So, it could be right in the front of your nose, although that's not a good idea if it's about to explode, but it's too small to see. That's how I think about bubbles, and how they break apart. It happens on very, very short timescales. Everybody else in my department studied big-scale physical oceanography. [Figure 2] is a log-log scale of time and length, so we have microseconds down there at the bottom and years up here on the seconds scale. The lengths go from micrometers, millionths of a metre, all the way up to approximately the size of a planet. The problem was that my PhD was down in that left-hand

© OUGS ISSN 2058-5209

Figure 3 Antarctica comes closest to land at Chile.

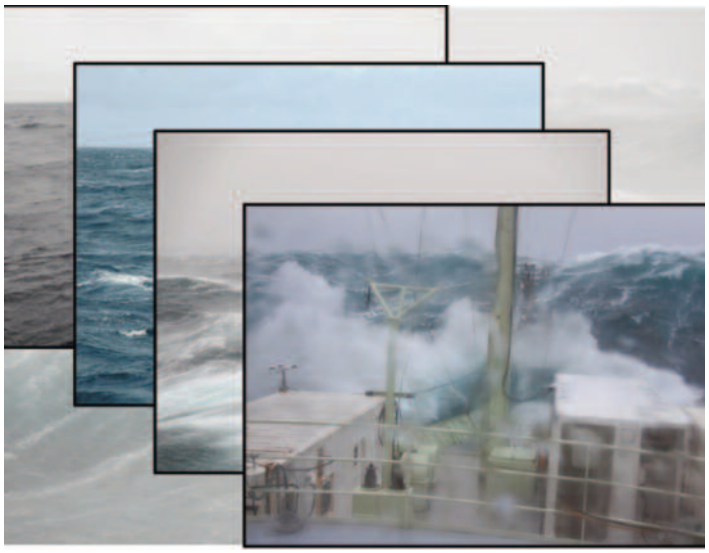
corner, where very, very small things happen very, very quickly, and the others were all up here. Gravity waves are waves on the ocean, [and] are somewhere in the middle. Small-scale mixing and PIES (pressure sensitive inverted echo sounder) are also in the middle. Then, going up and up in scale you get to Rossby waves, cyclones and large-scale waves. The problem was that I "thought about everything down here and they thought about everything up here". This is a quotation from [J. R. R. Tolkien's] *The Lord of the Rings*, and you may remember that when the hobbits, who are very small, are running around and they go and meet the Ents, who are the tree people [and who are] slow and think about things slowly. At one point, when they are running around this Ent Treebeard, he says, "That doesn't make sense to me. But, then again, you are very small". This is the problem with the sort of science that I do — that we're faced with this enormous challenge: There are small things down at the bottom, there, but the things that we're interested in are usually up there in the top right, and we somehow have to connect those things together and it is hard work. That will be a theme which runs through this [talk] — how you know that something tiny matters to something so enormous, that you can't make an obvious connection between them. We have to have a go!

If you are an Earth Scientist, a great way to look at the planet is that it is composed of five separate systems, organs, if you like, or components of the engine. They are the biology, the ice, the rocks, the atmosphere and the oceans — [all] massive systems that were traditionally studied separately. And what we're discovering as we go along, is that it's the interactions between those things that really make a difference. They are not studied separately any more, and the most interesting things are happening at the boundaries [where one system meets another]. The atmosphere is a massive [system]. The ocean is a [another] massive [system], and what happens at the surface is that you have one very thin layer, where things [processes] go from one to the other, where those two massive [systems] touch. That can be energy, momentum or gases. All of that depends, to some extent, on what that boundary looks like, what it's got in it, what is it, what it is doing? That's where you find bubbles, waves and turbulence, sea spray and aerosols. What I'm interested in is this boundary layer of the ocean, where these two massive [systems] touch — that's the place to learn about things [processes] going from one to the other, because they have to go through that boundary.

This is the southern tip of Chile [pointed out on a map; Fig. 3]. It's the place where Antarctica comes closest to South American land. I spent a month on a ship in that part of the ocean a couple of years ago. This is the sort of weather you get. It is a really intense area of the ocean. As well as the 'Roaring Forties', there are huge great storms that come through, very fast winds that go round and round the Southern Ocean. You get lots of storms, rotating storms, as this area is on a latitude on the planet, similar to ours [in Britain], so the Coriolus Force matters a lot — you get rotating storms, whipping up very fast winds. The winds push on the ocean surface and push up waves and eventually the waves break. You may think about breaking waves looking a little bit like this [a series of wave slides were shown; Fig. 4], but when I think about breaking waves I think about them looking a little bit more like this. This is the underneath of a breaking wave. This is a guy [with whom] I worked in California, for scale. This plume stuff is the breaking wave, so when you see the foam patch on the surface that is left after a wave breaks, it's not the tip of the iceberg, it's the foam on top of the bubble plume. The bubble plume is enormous underneath and there [are] lots of things going on. This is just the plume from one, actually a plunging breaker near the coast in California, but there [are] loads of bubbles in there that you don't see from the surface. If you zoom down even further into this plume, what you see is a lot of turbulence. The water is getting mashed and stretched and squished. If you put bubbles in turbulence, they do this: you have a bubble that isn't spherical to start with, as it's being pushed and stretched by the water, and as it continues to get pushed, it may well get stretched so much, that it breaks, and one bubble breaks into two (Fig. 5, *opposite*). So when you zoom down from a planet and you look at the processes going down and down, somewhere down at the bottom of it, one bubble breaks into two, and a new bubble is formed in the ocean. Underneath breaking waves there is lots of turbulence and this is how bubbles form. This is the start of the story.

So, I said I was interested in bubbles on the ocean and the thing about the ocean is that it is different in different places. It doesn't look the same everywhere. If you look at the planet, there [are] all kinds of different temperatures, different salinities, different nutrient levels. Lots of things are different in that ocean. So sometimes, it looks like this and sometimes it looks like this [referring to series of photos of ocean states], and you are starting

Figure 4 Breaking waves and different sea states.



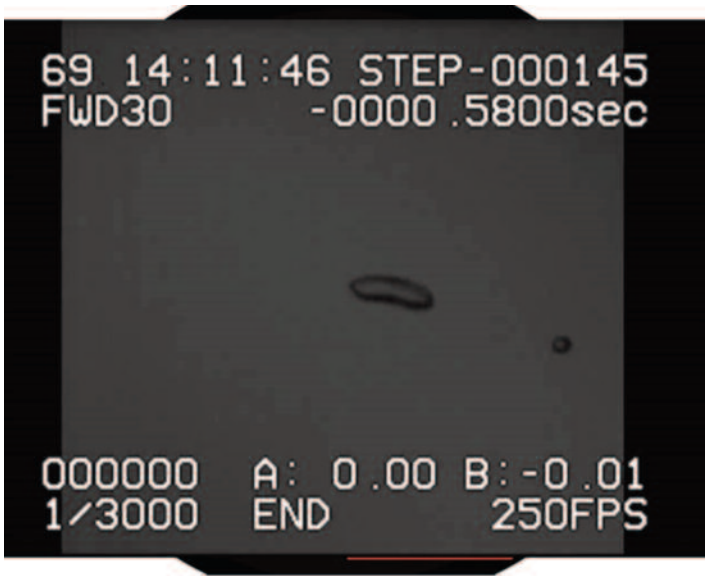


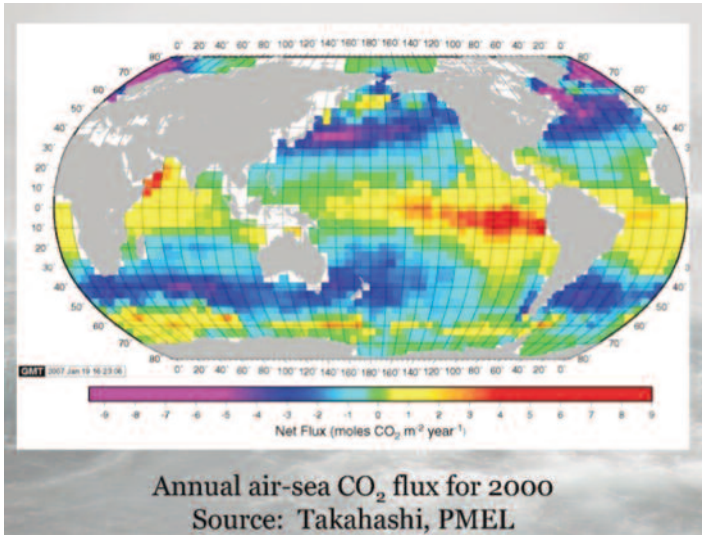
Figure 5 A non-spjerical bubble.

to get white caps. Sometimes, it looks like this and occasionally it looks like that. So the problem is that if you want to know about this surface, doing different things in different places, you have to characterise those different places.

Why care about bubbles?

Why does anyone care about bubbles? I said that they're at the interface. There are lots of reasons for caring, all of which you can demonstrate with a glass of champagne, but I'm only going to talk about two of [these reasons]. The first one is these exchanges or changes in the chemistry, both of the atmosphere and of the ocean. One of the biggest things we see now [e.g. in the media] is of carbon dioxide. About a third of all the carbon dioxide that we humans are putting up into the atmosphere is being taken down into the ocean. It's making the ocean less alkaline. This is a map of a year's worth of the ocean breathing carbon dioxide (Fig. 6). The red regions are where carbon dioxide is being given out, and the pink and blue regions are the places where carbon dioxide is being taken in. That's all happening at the sea surface. What we're interested in is how carbon dioxide is coming and going. We are just about to get a huge amount more data. This is

Figure 6 The breathing ocean.



really hard-earned data, which is difficult stuff to measure — watching the ocean breathe is hard. We are about to get a lot more information, not just over the ocean, but [also] over the land. You may have seen, three or four weeks ago, [that] the orbiting carbon observatory finally made it into orbit (Fig. 7). Five years ago, this should have been launched. And as it was launched, something went wrong towards the top of the flight path and the whole thing blew up and ended up in the ocean, so orbiting carbon observatory number one should have been above the air for five years now, but it didn't happen and so we had to wait five more years, and three weeks ago, this thing successfully went into orbit — so it's zooming over our heads now, in a low polar orbit. It's got spectrometers on it that are there for one job only, to monitor carbon dioxide. So I'm hoping [that] by this time next year, or the year after that, the pixolated map of the ocean breathing I just showed you will become out of date, as we'll have information from this instrument, which shows both the land and the ocean breathing over the course of a year in huge detail. So that's something to watch out [for] in the future that I'm very excited about.

Orbiting Carbon Observatory (2)
Jet Propulsion Laboratory
California Institute of Technology
JPL Home News Images
Home Mission Observatory Science Galleries News Glossary
Spacecraft
OCO-2 is based on the previously launched Orbiting Carbon Observatory (OCO) satellite and will carry a single instrument, consisting of three high-resolution grating spectrometers (instruments that measure properties of light within the electromagnetic spectrum). The Orbital Sciences Corporation LeoStar-2 multi-mission spacecraft bus, used successfully on missions such as SORCE and GALEX missions serves as the on-orbit service platform for the OCO-2 (Orbiting Carbon Observatory-2) three-channel grating spectrometer instrument.
more

Figure 7 The orbiting carbon observator (Internet source: reproduced for educational purposes only).

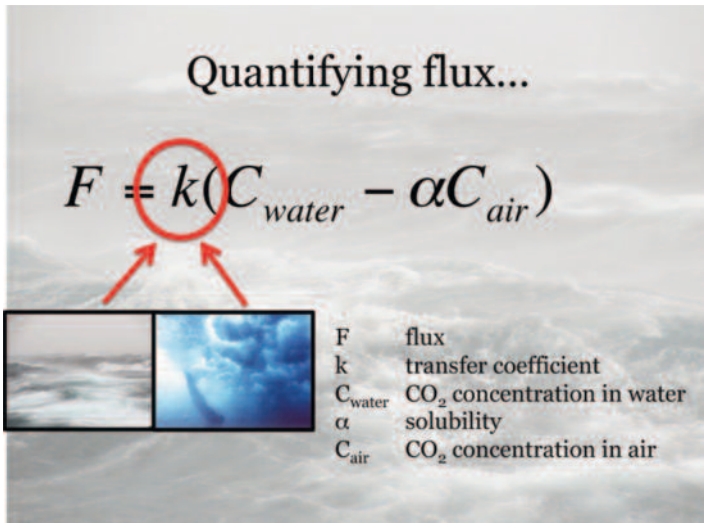
So, we're interested in how the ocean breathes, that's one reason for studying that interface, because that's where the ocean breathing happens.

The other [second] thing that we're interested in is breathing out — not just gases going down — [for] there [are] also gases coming back up. Some of them are sulphur compounds, which are important for cloud formation, for example, as they change the radiative properties of the atmosphere. You know that if you take a fizzy drink and you hold it under your nose, you will feel the tiny bubbles, spitting little particles up your nose. All those white caps, those breaking waves out on the open ocean, are also spitting tiny particles upwards, and they're drifting up into the atmosphere, contributing sea salt and organics and various other bits and pieces into the atmosphere — and [these processes are] also important for cloud formation and [for] how light travels through the atmosphere. These tiny particles are called aerosols. So we have aerosol production and we have carbon dioxide and all the other gases, [and] that's why we care about bubbles and why we care about the surface layer, as we want to understand where that process happens and how it happens?

Here's a little cartoon of a breaking wave *[a short video was shown — Ed.]*. So if you like storms, the nice thing is that you can stand on the deck of a ship and look out, over the surface of the ocean, and you are looking at a scene that seafarers have seen for centuries; they've looked out at the foam patches on top of the ocean, they've looked out at waves. Humans are very familiar with this scene, but none of those people, unless they were very unlucky because they'd just fallen off the back [of the ship], ever had the chance to look underneath at what was happening, just a few metres away, just hidden from sight. So here's what's going on, just hidden from sight. You get a breaking wave at the top, the wind pushes on the waves, up until the point when they break, which is quite complicated all by itself. Then you get a breaking wave that traps a lot of gas just under the surface of the ocean, and as the turbulence generated by the wave gets to work on that gas, it breaks it up and one bubble breaks into two, those two bubbles break into four, and you have this cascade of bubbles breaking up in turbulence; and that [process] lasts as long as the turbulence lasts, which is maybe about a second. It depends upon how big the wave is. So then you've got bubbles and then what happens is the turbulence will carry some of those bubbles deeper down into the ocean. Some of them will be so big, that they will be so buoyant that they go straight back up to the surface.

So, already you have a sorting process: big bubbles go straight back up, smaller bubbles may get carried around farther down, so that they may be advecting. Once they are down in the water there may be gases that come into them, [and] there are probably more gases that come out of them, because the ocean is squeezing on the bubbles — so they may be dissolving. They may still be rising under buoyancy, depending how big they are, as very small bubbles only rise very slowly, as they basically just get carried by the water. The ones that make it back up to the surface form a foam patch, and as they pop at the top of the foam they may get replenished from underneath; but as they pop at the top, they are generating aerosols through different mechanisms and spitting these tiny particles up into the sky. So, that's the sum total of what's happening in a breaking wave; and these processes matter. The small things matter for the big thing, as I showed you on a map of a planet of carbon dioxide breathing. The places where all that gas and other gases are coming and going are places like this. It's the small processes at the bottom.

Figure 8 A 'simple little equation': solve for Flux (F).



The overall motivation for this is that we care about the ocean breathing, not just because it's a nice thing to know, [but because] it is very interesting scientifically and typically very useful for lots of things. The specific outcome is to improve weather and climate models, because where these particles are coming and going, where the inputs and outputs are, make a difference to the outcomes of the weather; so we're interested in that process — that's the 'why should I care?' thing.

Measuring of what's happening

We know that there are storms, and breaking waves and we want some measure of what's happening where, and as physicists like simple little equations. This equation is the simplest way of expressing it (Fig. 8).

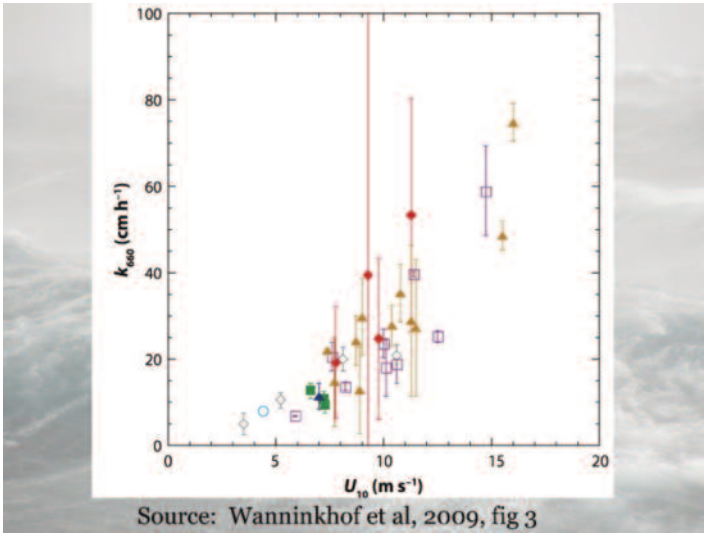
$$F = k\,(C_{water} - aC_{air})$$

Flux, F, is just stuff coming and going, moving through a boundary. The concentration of a gas in the air and the water matters, because if you have a supersaturated liquid, it will tend to give off gas to the air if the partial pressure is lower. So the relative concentrations of any single gas in the ocean and the atmosphere matter. The solubility of the gas [also] matters. And because physicists like simplifying things, we just put this '*k*' in the front, which is just a constant. So the flux depends on the concentration difference between the air and the water and then there is this mysterious thing, '*k*'. In this '*k*' is bundled up all kinds of physics. What weather people want is to know what '*k*' is [i.e. its value], because then they can just plug it into their models, run the models and then they will have a realistic output.

The problem is that '*k*' hides a lot [in it], an awful lot. Inside '*k*' [are] hidden: how many breaking waves are there? How big are the breaking waves? How big are the bubble plumes underneath? What's in the water? — there is all this science hidden away in '*k*'. But the fundamental point, in many ways my job, is to find out what '*k*' is, what one number is. We do all this science in order to find out one number, and that one number is the only thing that gets passed on up the [scientific] food chain.

This is the sort of plot that is very common, if you are trying to find out what '*k*' is (Fig. 9). You can image on a very flat ocean, where there's not much going on — smooth water; there's probably very little coming and going across the surface of the ocean,

Figure 9 Typical data plot for finding 'k'.



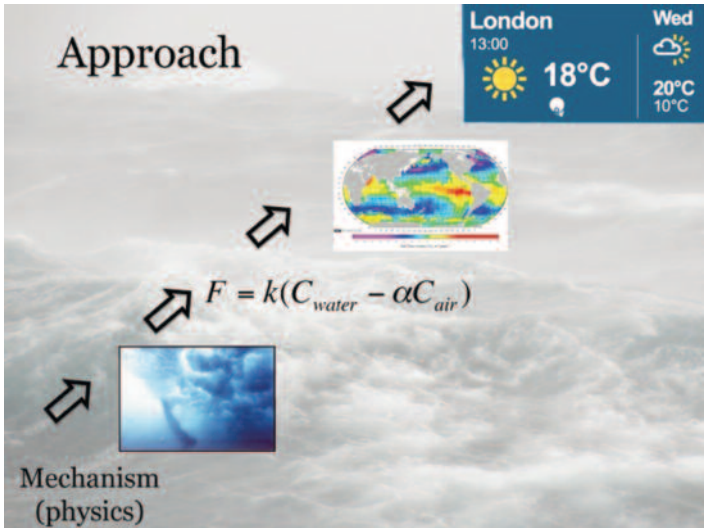


Figure 10 Ocean small-scale physics.

Figure 11 We want some parameterisation in the middle.

as nothing is really moving, whereas when the wind blows, the wind pushes on the water and pushes up big waves. The waves start to break and you get all kinds of mixing going on. So the first thing [to investigate], if you want to find out how much breathing is going on, would be to know how much the wind speed matters. This is that plot. So along the bottom we have wind speed in metres per second. It goes from 0 to 20. (If you work in knots, they are about double that.) And then this [other axis] is that '*k*', which quantifies the amount of breathing that is going on. So you can see that at very low wind speeds, there is very little going on, not much is happening, and as the wind increases, the amount of breathing increases, [and value of] '*k*' goes up. This is a summary of the historical measurements [up] to 2009. But there are enormous error bars on some of these [values], because [when] measuring breathing [it] is actually very difficult to get detailed measurements — so you get very big error bars. This is five years ago, but in the five years since [this plot was made, it] has been populated with a few more points, but the errors bars haven't really got any smaller.

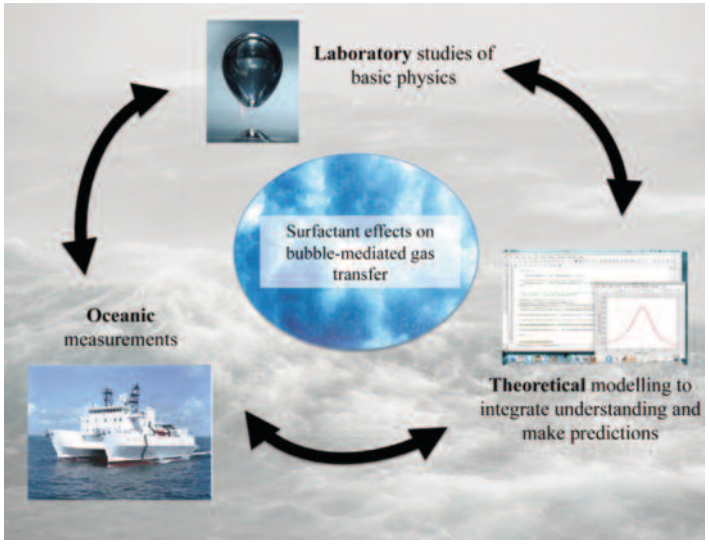
So, the problem is that just using wind speed to try to work out what '*k*' is, doesn't work. It is sort of a good first pass, but there [are] clearly all kinds of problems with it. Apart from anything else, 20m sec^{-1} (35–40 knots) [is typical] — it does that on the ocean all the time, [and] is not [an] extreme condition. Yet you can imagine, if you had a hurricane or a big storm, really windy conditions, that [would] probably make a much more significant contribution to the exchange of the gases and the particles. So the problem is, up here in 2009, until a year ago, that was as far as it went, yet we know that over many parts of the ocean there are big storms that fill in this space here. So the aim of my work is to understand the physics that goes into that '*k*', to try to make this graph a bit more understandable.

How it works

So, this is how it works — to go back to that scaling thing (Fig. 10). There [are] some small-scale physics down there, there's a weather forecast up there. The traditional response has been: We want some parameterisation in the middle (Fig. 11). We want some simple thing that encapsulates everything that's going on down below and takes it up to a size that a model can deal with. [For] however fast the Met Office's supercomputer is — *[digression about the size of the Met Office's supercomputer — Ed.]* it is surprisingly small, actually, now not much bigger than this stage, [although] it used to be enormous and has physically got a lot smaller; so you've got supercomputers up there [pointing to upper right of Fig. 10] — there [is] this kind of bottleneck in the middle [pointing to middle of Fig. 10], where you're trying to understand enough of what's down here to pass on the relevant bits to get to the breathing bit [pointing to global breathing map in Fig. 10], which can go [in]to a model. There [are] lots of difficulties with this approach, but it's sort of the best we have [in which] the linear small thing makes [a] slightly bigger thing; [the] slightly bigger thing makes [a further] slightly bigger thing; [which in turn] makes [a] slightly bigger thing bigger than that — you have to step up, and it's hard and it's time consuming, which is why no one's really done very much of it.

So, the way that we try and do [this] is a mixture of things [research steps]. The way that you try and get at this science is a mixture of laboratory studies of basic physics to work out what bubbles do, in my case, and theoretical modelling to try and test whether the physics you think you've understood is actually going on — and then, [to take] measurements out on the ocean, to test the real world. So you do this kind of science, you go round and round this circle, and each time you go round, you hope that you find out a little bit more (Fig. 12).

Figure 12 The bubble research circle procedure.


Laboratory studies of basic physics
Surfactant effects on bubble-mediated gas transfer
Oceanic measurements
Theoretical modelling to integrate understanding and make predictions

I am not going to talk a lot more about laboratory studies, but I'm just going to give you one example of the sort of thing you can do in a lab; this seems a million miles away from the global ocean, but it does actually make a difference. So I'm going to play a video of a bubble breaking off from another. You must imagine an enormous straw with the bendy bit under the water and if you blow down the straw, then this is the process of a bubble breaking off, away from the end of the straw, [which] happens in less than a millisecond. But what happens at the moment that it breaks off is that the bubble sends out a 'ping' sound, and this, on the right here, is the pulse of sound sent out (Fig. 13). You can see [what] shape the bubble is at different points on that sound wave, and the reason that is useful is that it's very difficult to go under the wave and count individual bubbles, but if every new bubble makes a sound at the moment that it is born, then you can listen to that sound and work out what the bubbles were. So, this is the sort of laboratory study you can [do] to study basic understanding of bubbles in the ocean. And you can recreate the ocean and try these experiments in very salty water, water with lots of biology in it — all kinds of [permutations]. This is just one example of why a laboratory study would be useful if you were looking at the global ocean, as the basic physics at the bottom of it is still not very well known. Underneath there — where those bubbles are breaking apart — it's very noisy and you can hear all those sounds.

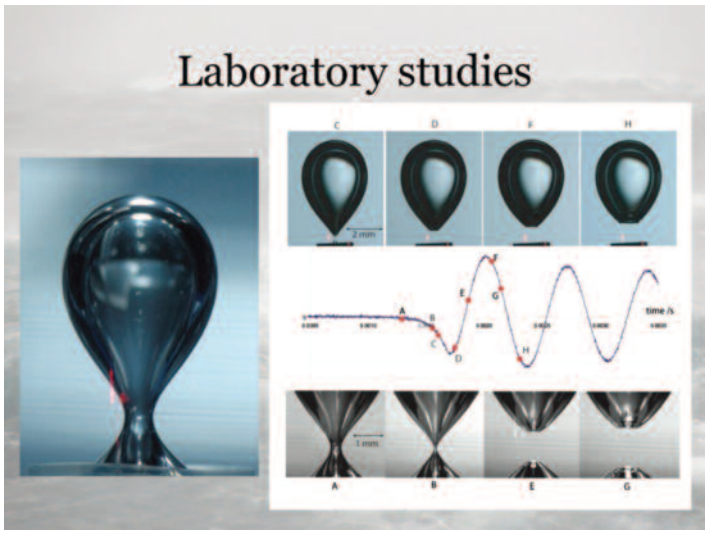


Figure 13 A bubble 'pinging'.

But most of the time recently, I've been doing ocean-going studies, where you actually go out to the ocean, look at the ocean surface, measure how it's breathing, see what's going on and try [to] piece it all together. So, I'm jumping about the size scales quite a lot here, and the reason is, is that's what it's like. I could do this talk, and I have done, where its completely logical, and you start with the small bits and logically progress to the bigger bits, but I stopped doing it because it's not representative of the way the science works. The way the science works is that you get bits of information at different scales and different times and you have to put them together. So, I deliberately started to give a slightly more confusing talk, because we don't know the answers and this is how we're finding [them] out. We're jumping about between the different size scales and trying to piece it all together.

Figure 14 The research ship RV Knorr.

North Atlantic escapade

So, the most recent escapade was to go to the North Atlantic last October and November. This is the ship *RV Knorr*, out of Woods Hole, an American research ship (Fig. 14); there were not this many people on the ship. There were 11 scientists and 20 crew [members], and we were on that ship for six weeks and we saw land once. The only reason that we saw land once was that something had broken and we had to go into calmer water off the Gulf of St Lawrence to get it fixed.

So, the rest of this talk is going to be about some of the information that we found and how we found it out, because one of the things that I think people don't talk about often enough, is 'how you get there'. It is not the case that you take a big textbook and turn to page 23 and here is how the ocean works. That's not what's going on. We're struggling through, so this is a tale of how we're struggling through this particular problem. So, the *RV Knorr* [sailed] out of Woods Hole, [and] we met her in Nuuk in Greenland. Here's the map with the southern tip of Greenland and here's Canada and a bit of America, and this is what we did over six weeks in the North Atlantic Ocean [Dr Czerski pointed these places out on a map slide]. We decided where we went based on the storms, trying to get ourselves right into the middle of storms so that we could measure lots of different wind speeds, lots of different conditions, and give ourselves the best chance of separating out what happens at low wind speeds and in calm conditions, and at high wind speeds and everything in between. We started up there in Nuuk and then we scooted around down here, through the Gulf of St Lawrence, which was the only time we saw land, and then we actually didn't finish in the middle of the ocean but we finished over there. This is what was on the ship; we were very privileged on this cruise, as we had the whole ship to ourselves; effectively we could do what we wanted with it and nobody else wanted to come. (Quite often when you go to sea there are spare berths on ships and people will come along, as they have got a few extra experiments or some useful things they could be doing, or they want the experience. Nobody wanted to come on this cruise; six weeks in the middle of the North-Atlantic, in storm season, in what turned out to be the most intense storm season in the past 20 years. Nobody wants to do that. But there we were.)

There were people from all of these universities. Most of the people on the ship were measuring the ocean breathing process. They were measuring carbon dioxide, di-methyl sulphate,

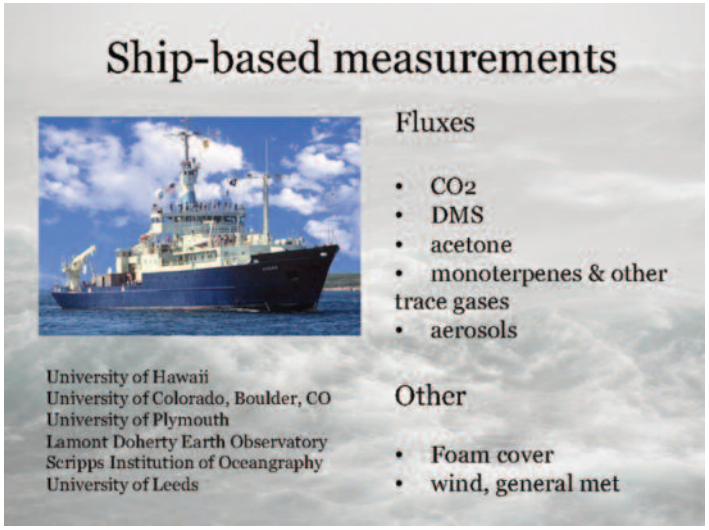


Figure 15 Many universities, many measurements.

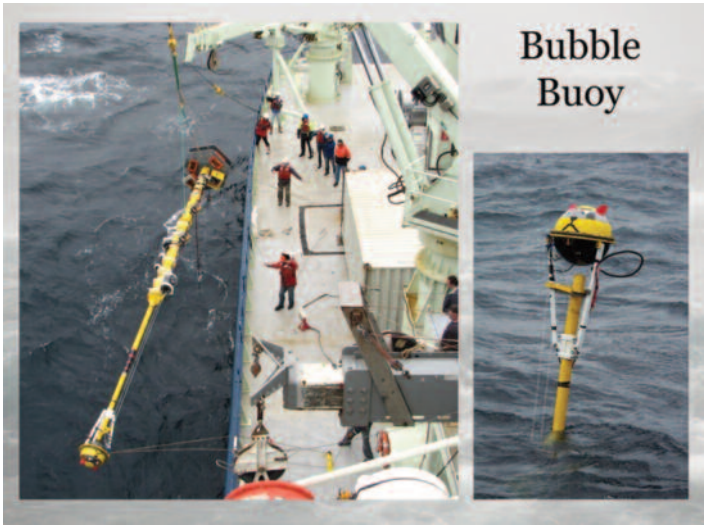


Figure 16 Dr Czerski's buoy, 'Bob'.

acetone, monoterpenes, [which] are things that come off pine trees *[e.g. from fossil forests — Ed.]* — it turned out there were almost none of them, [although] they are occasionally around in small quantities; and aerosols, which are the small particles coming off the ocean. Our job — my bit of it [in] the team I was part of — was to look at the sea state, what the ocean was doing and to look at the bubbles, to look at the wind and to quantify what was going on underneath the water in order to try to link it in with the processes, because we were in the middle of this breathing process. There is no more visceral way to be experiencing this (Fig. 15).

'Bob' the buoy

So, that was everything that was on the ship *[meaning the various pieces of equipment — Ed.]*. That was everyone else's stuff and this is what I took along (Fig. 16). It's terrifying when you write a research grant and you draw a picture of this thing and it turns up and it's frightening — this buoy, this 11m long thing here. (The reason why I say 'bu-ey' is first of all, because I studied oceanography in America and secondly, it's wrong to talk about throwing 'boys' off the back of a ship; so they are 'bueys'.) An 11m long buoy, bigger than it looks on that picture — I mean just a monstrous thing. And we would put this over the side of the ship and spaced out along it were different devices for measuring bubbles. The idea was that this thing [buoy], we would put it out before a storm, when it was relatively calm, let it float freely, then scoot along and scoop it back in afterwards and download all the data.

That was more or less how it all worked. It may have looked like a monster on land, but when you put this thing out into the middle of the ocean it suddenly looks really small, and because we all went a bit potty, somebody put a face on it (*see* Fig. 16 *right*). We had a competition, my friend Adam Rutherford got very excited about this and [said] that we should think of a name for it, a competition. So, a few names were suggested. It got called 'Bob' in the end, which I thought was quite clever. My favourite was actually 'Buoyoncé', which seemed better. They said on the ship it was too grumpy to be a 'Buoyoncé'. I think that they were just being prejudiced. My other two favourites were 'Pike', because it was a stupid boy, and 'Del boy the globetrotter'.

This thing was put out into the ocean, with its sad little grumpy face. (By the way, even though it had been out in 80-knot winds its ears were still sticking up — amazing.) This was what was on the buoy. When it floated upright in the water, the water came about half way up that long thin bit. Up at the top, in that dome, there was the camera, looking down at the white patches of foam out on the surface of the ocean. Just below the surface of the water there's a high-speed bubble camera that was taking very fast images of any bubbles that were near by. That black image [showing one on a slide] is fairly typical, because most of the time there weren't any bubbles.

The next two things down [along the buoy] are two resonators, [which are] acoustical devices that let you measure the size distribution of bubbles — how many big ones and how many small ones. Right at the bottom, there's the sonar, looking up and out. This is one of the sonar images, so you can see the buoy there, tilted, as it would orientate itself into the wind, by tilting itself. You can see the sea surface. You can see patches of bubbles under the sea surface. The reason that sonar is very useful at looking at bubbles is that they respond very strongly to sound. If you're looking in sound, bubbles are basically like fairy lights. So, if you want to know where bubbles are, sound is the way to do it, which is why we are using sonar. So you get an overall picture of what was going on underneath the wave. Then we could use the resonators and cameras to look at the specifics of different places within that wave, which is something that no one has done before — so I was very fortunate to have the opportunity to design this. Tied in with all that, at the top, that's the surface of the wave, so there were some wires going up and down that thin bit, which let us measure the height of the water relative to the buoy at any one time. So we could see where the peaks and troughs in the wave were and correlate [these] with everything else.

So, this was the point of this buoy, to put it out in the ocean, to let the storms wash over it and then to compare that data afterwards with all the data about the breathing. The ocean can be a bit like this (Fig. 17, *overleaf*). I hope no one [here] gets seasick. The light blue patches you can see underneath, they are the plumes of bubbles. People didn't really get seasick as it wears off relatively quickly. This was the stormiest day when we were out there and was the St Jude's storm when it got to the UK; I think that it was the 30th October [2013]. The winds were up *c*. 70–80 knots. The significant wave height was an average of 10m, going up to 15m. This was as good as it got.

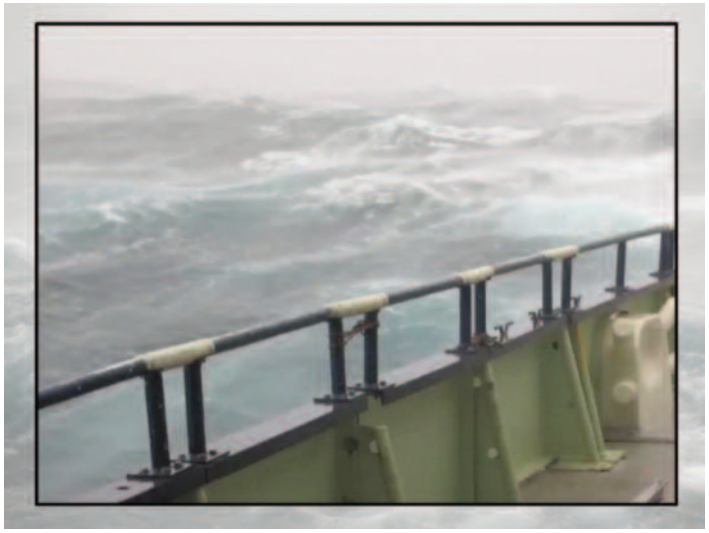


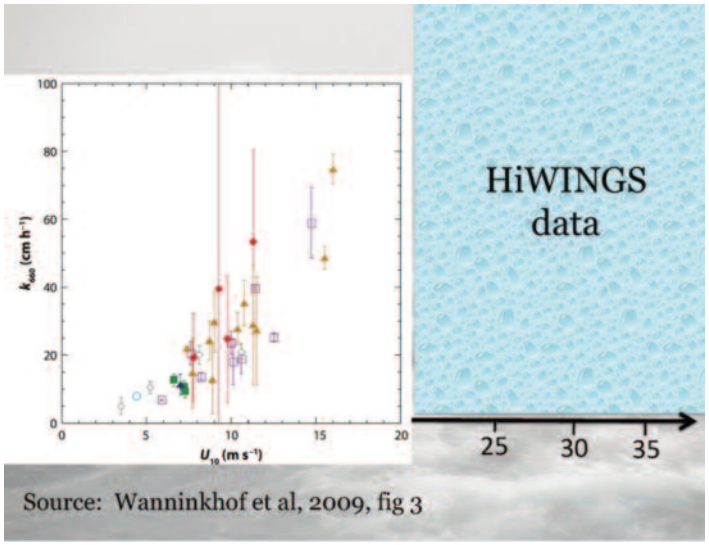
Figure 17 "Most of the time it wasn't that stormy."

I've never seen anyone as happy as the chief scientist, who woke up to all of this, because this [the weather conditions just described] is what we went to sea for. All those plots I showed you, where the measurements stopped at a stiff breeze, this is what we wanted to make up the gap. So, we put this buoy out — most of the time it wasn't that stormy — although that [i.e.Fig. 17] was a good day, and then we let it float free. The idea is that we would fill in the data here, so this blue patch here, that's the graph that I showed you before (Fig. 18), showing the amount of breathing that happens as the wind speed increases, and this was almost entirely uncharted territory. The data are still being analysed, but it turns out that with these fluxes, different gases do different things: some are more soluble than others, so that plot has a different shape. My collaborators who did the gas fluxes are still in the process of analysing. But we've really extended out the range of things that were measured, and it's thought that these storms are some of the most significant mixing events. Maybe they're not. We are still trying to work this out, but filling in this gap is really important.

The data — what 'Bob' recorded

Now I am going to go through examples of the data. By the way, there is no answer to the question asked at the start 'What difference does a bubble make to the ocean?' We're still finding out,

Figure 18 Filling in the data.



but we have the data to find out and I can show you some of that data and some of the correlations — but we're still picking it apart, so don't expect a rabbit out of a hat at the end! We haven't got there yet. The foam camera data is still being processed. One of the frustrating things [about] going to sea is that you come back with so much data — 20 terabytes in my case, which is a frightening number. It takes a very long time to process it all. Even though we came back seven or eight months ago now, we're still wading through the data, because there's a lot to do. The bubble camera itself — there's not a lot you can see on this as most of the time the bubbles are quite small. We have loads of data like this, which [are] just snapshots of bubbles close to the surface, underneath the breaking wave, so we can measure lots of sizes of bubbles from that (Fig. 19 *centre panel*).

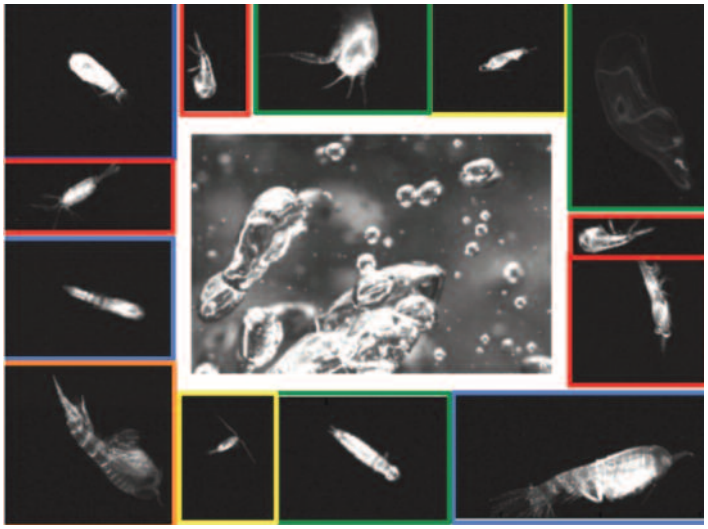


Figure 19 Measuring different sized bubbles.

It turned out that the best pictures we got weren't of bubbles, which I hadn't anticipated at all. The post-doc whose doing it, an Iraqi who doesn't know much about the ocean but is very good at electronics engineering, came and said, "I've seen fish". He hadn't seen fish. He'd seen these (Fig. 19 *surrounding panels*)! These pictures of copepods should be used by biologists. This is clearly the way to do it. We saw lots of other things floating in the ocean as well as bubbles.

[Now], we do know something about very new bubbles underneath breaking waves. Because of the way the physics works, we expect a certain size distribution at the start (Fig. 20, *opposite*). This is radius along the bottom, on a log scale, and number of bubbles pre metre cubed — basically a complicated unit, but [representing] how many bubbles up the side. This is the moment of bubble formation, right at the beginning of the turbulent bit, not very many big bubbles. There's a very specific slope as you get smaller and smaller bubbles, you get more of them, and there's a point there, called the 'Hinze Scale', and the slope changes and then you get even more [bubbles] as they get smaller. No one has really convincingly seen that turnover, as it is dropping off the line a little bit. So, maybe the ocean isn't pure small bubbles — but that's always three points before the resolution of any instrument you're measuring it with, so I'm a little bit hesitant about that. So, this is what we expect to see: the new bubbles form and we do know some physics about that formation process. We haven't got much data about the initial bit, but maybe we will.

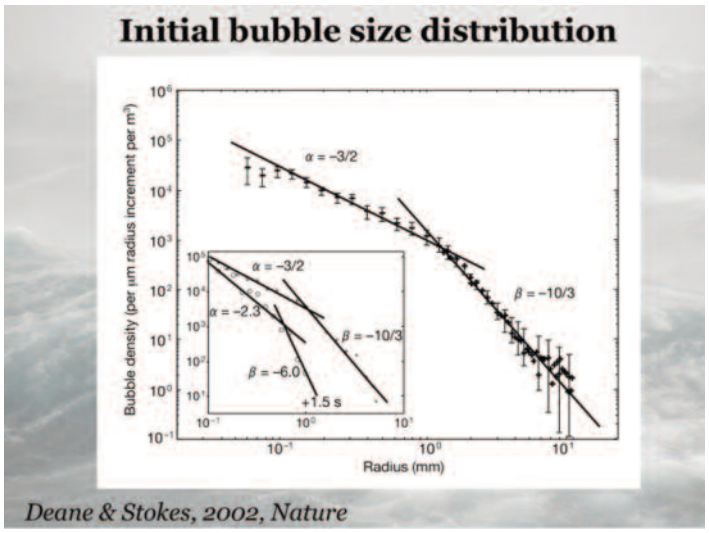


Figure 20 Bubble size distribution: log scale of bubble radii (x-axis) and bubble density (y-axis), showing the 'Hinze Scale'.

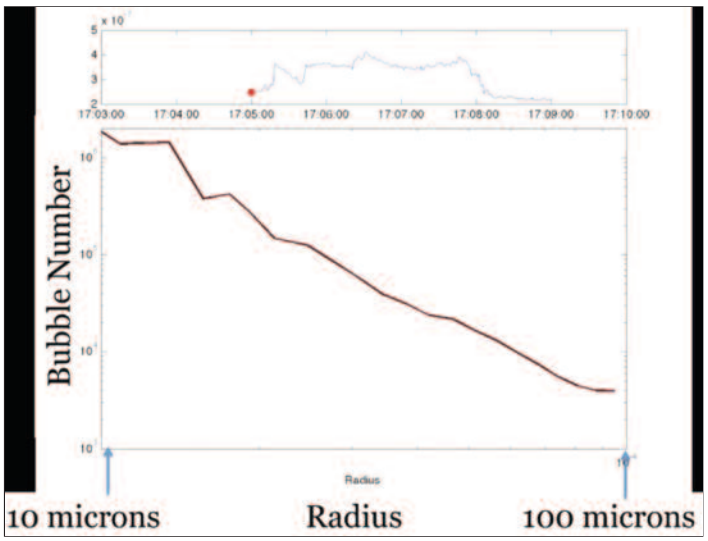
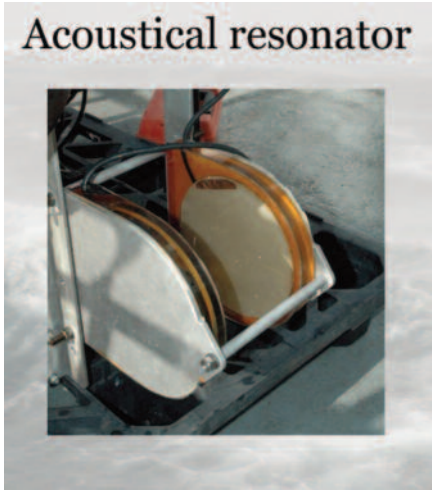


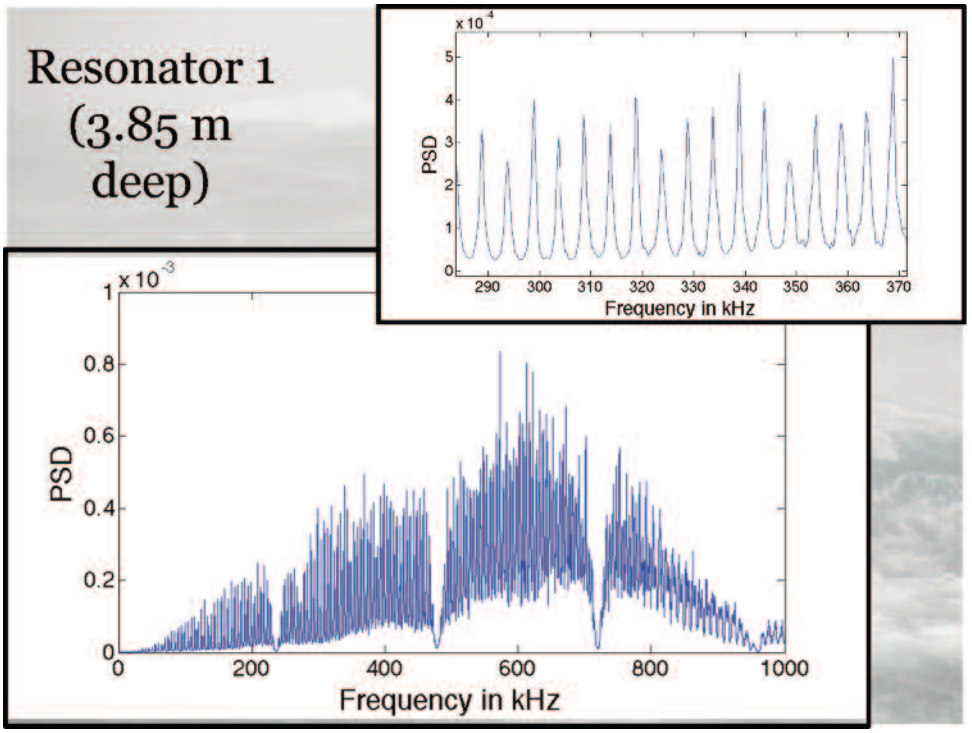
Figure 23 Graph plot of the data measured by the acoustical resonator.

The acoustical devices looked like this, those resonators that are measuring bubble size in a different way (Fig. 21). This is basically a portable echo chamber and sound bounces between the plates. You get lots and lots of echoes — broadband sounds. You get echoes at lots of different frequencies. Bubbles absorb sound, depending on their size, so big bubbles, like big bells, absorb and produce deep sounds and small bubbles absorb and produce high sounds. So by listening to different echoes coming and going, you can tell how many bubbles there were and how big they were. This [graph shows] a little bit of the data you get (Fig. 22). Each one of those peaks is an echo, and the peaks go up and down as the bubbles go through. So we can tell how many bubbles of which sizes were there — that's what the resonators were doing. And you get this kind of plot at the end (Fig. 23). This is similar to the thing I showed you before [i.e. Fig. 20]: small bubbles over there [Fig. 23 *left end*], big bubbles down here [Fig. 23 *right end*], bubble number up there [Fig. 23 *y-axis*]. As waves go past you can watch the numbers of bubbles coming and going. So that's lots of useful information.

The sonar images are lovely, this is Adrian, who is part of the project and this is some of his data (Fig. 24, *overleaf*), which he got last week [before this lecture]. The thing I love about these images is that you can really see what's going on. The sonar looks up at the surface of the ocean. It can see strong reflection off the surface, so the top plot shows the surface waves going past the buoy. This one (Fig. 24 *lower plot*) is even better, because what happens is that the ocean was going up and down, a wave breaks, and you see the bubble plume drift deeper and deeper, gradually into the water (Fig. 24 *right half*). We are finding that the bubble plumes last between four and five minutes in most of the conditions that we're looking at. You can see that they gradually get deeper and then they die away. You can see the structure of the bubble plume, and what we are also going to be able to do, but we haven't got the data [for it] yet, is to see with the foam camera what the foam patch looked like

Figures 21 and 22 The acoustical resonator and a graph print-out showing the sort of data that it measures (how many bubbles and what size they are): small bubbles on the left end and big bubbles on the right end.





© OUGS ISSN 0143-9472

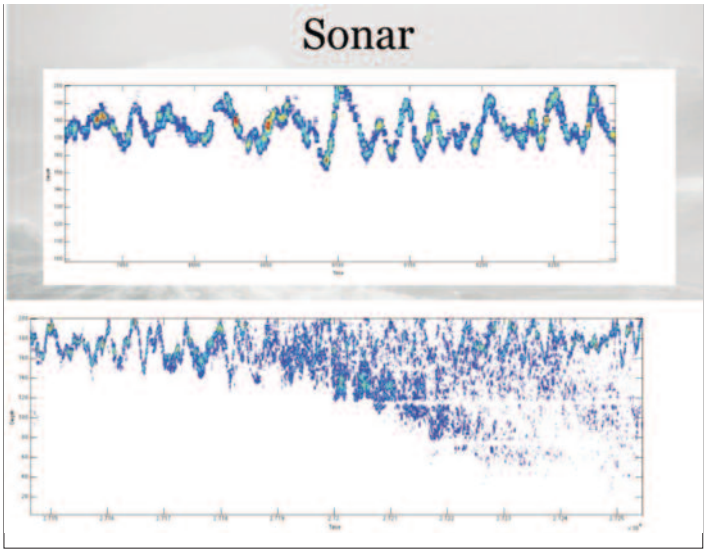


Figure 24 Some of Adrian's sonar data.

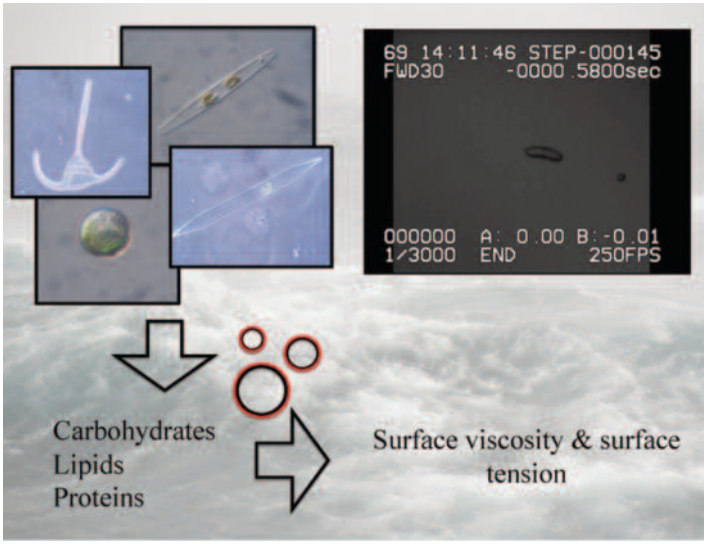


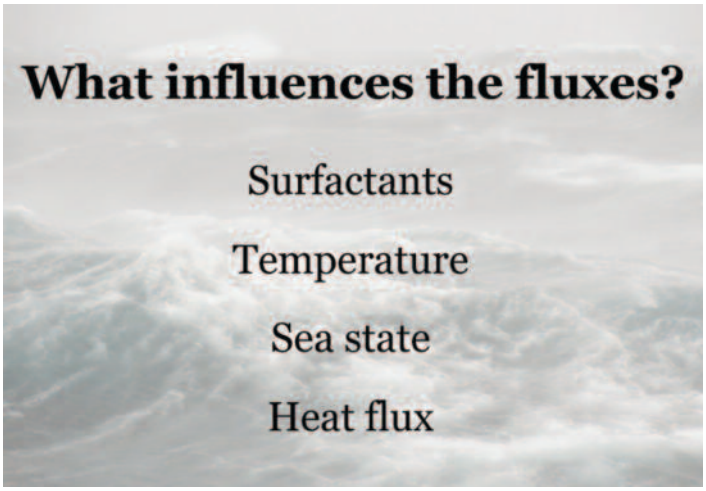
Figure 26 'The jigsaw puzzle.'

on the surface. You can use satellites to measure the amount of foam on the surface of the ocean. You can look down with a satellite and see the foam patches and then you use these data to know something about what's going on underneath. You can start to piece the jigsaw together.

So, this is what the data look like. This is the way it might vary, depending on what's in the water, what the water is made up of — different things will happen (Fig. 25). Surfactants are natural ocean bubble bath. Small organisms in the ocean, phytoplankton specifically, will produce carbohydrates, lipids [and] proteins, and these things act as natural bubble bath. That makes a difference to the bubbles and it probably makes a difference to the fluxes. Ocean water temperature varies a lot — from 2°C to 30°C; that [variation also] seems to make a difference to bubble formation. How big the breaking waves were, [and] direction of the swell compared to the wind, all that makes a difference to the bubbles. Heat flux, whether the ocean is warmer than the atmosphere, or the other way round — that [too] seems to make a difference to the foam patches on top. We're still trying to figure that one out.

So, these are the sort of jigsaw pieces were hoping to use to glue these data together (Fig. 26). This is the surfactants thing (Fig. 26 *upper left*). Lots of various phytoplankton producing this 'crud' — a technical term! The 'crud' coats the bubbles

Figurde 25 The variants.



and changes not only how they break apart and join together, but [also] how easy it is for gases to get into and out of them, and how they pop at the surface (Fig. 26 *lower left*). This is the biggest mystery of the lot; the surfactants and I haven't got very far with that one yet, even though I started a project three years ago to try and figure it out (I got distracted by other things). The surfactants potentially matter a lot.

We know those things matter a lot. We can measure these things and that all makes a difference to some of that [process].

The challenge now

Our challenge now — and it is a big task, which is why we haven't finished it yet — is to piece this together in a meaningful way. This is a classic example of the science that is going to become more and more common in the next few years. We are done with the days where you had two variables and you plotted nice points on a line, and you drew a straight line through those points. That's not the way science works any more, and it's especially hard for a physicist to come to terms with because physicists do like their graphs with their straight lines. The biologists are actually way ahead of us. Geneticists and people have to deal with this all the time. These are messy data — there are no simple correlations. It may well be that when we do some analysis that makes sense of all of [these data] our brains might not be able to intuitively get hold of all of this, because there are too many relationships for our brains to make sense of all at once (Fig. 27, *opposite*). So, this is the era of complex systems science. I think that the way this will be solved is by using new methods for looking at the structure of data, looking at the relationships between lots of variables all at once. And there may not be a simple story that comes out at the end of it. In fact, if there was, it would already have been discovered and there wouldn't be a point for doing any of this [research].

So this is the task for the next year for us. When we have understood bubbles, the idea is that we will have a better understanding of the parameter '*k*', that you may remember from some way back [at the start of the talk]. This very small jigsaw piece is then what we will pass on to big weather and climate calculators, like the Met Office's 'Hadley Model' [HadCM3] (Fig. 28, *opposite*).

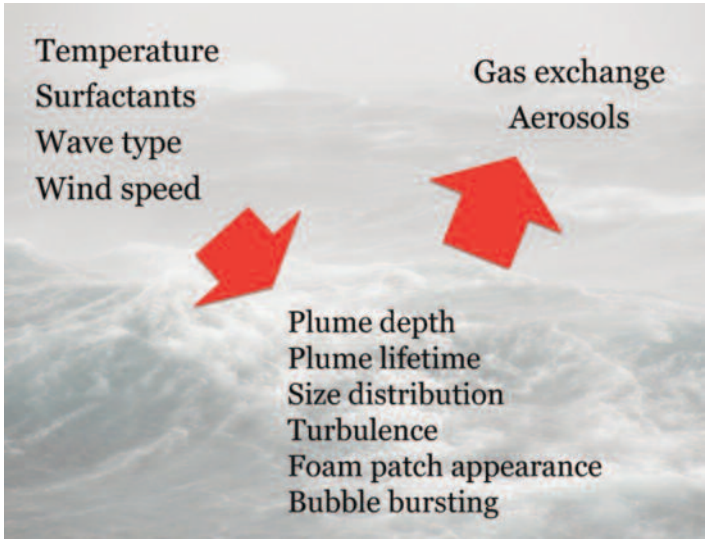


Figure 27 'Messy data' — 'too many many realationships to make sense of all at once' — 'no simple correlations'.

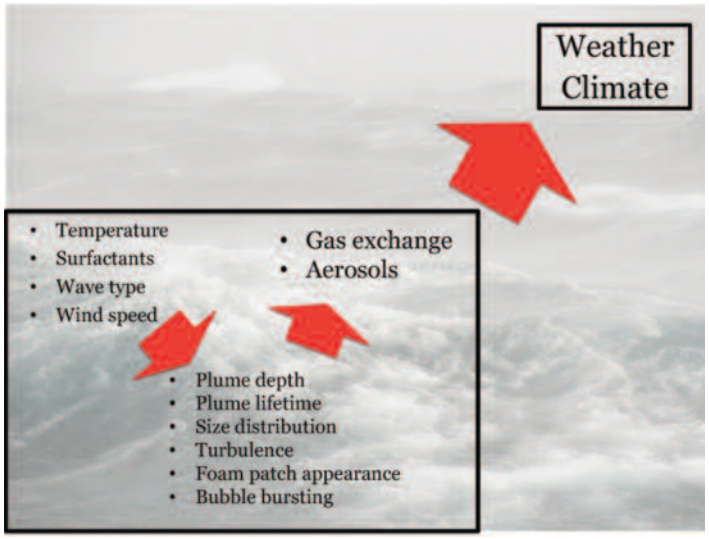


Figure 28 The parameter 'k', a very small jigsaw piece to pass on to big weather and climate calculators, like the Met Office.

And whether this is possible or not, nobody knows. We know there's a lot of complexity down here. We don't know whether it's possible to encapsulate it or how well it's possible to encapsulate it, to pass it on up the [research] food chain. We do know that if you get better details down here (Fig. 28 *lower left*), they make regional forecasting more accurate. But how good the details can be is not clear. It's not a case that more detail is always better and we need to think about that, but we might as well do it by finding out.

So, this is a 'to be continued' story (Fig. 29). We've got a lot of data. We've made the measurements. We're piecing it together and it's probably not going to be a tidy story by the time we've finished with it, but if we want to understand our planet, how it breathes, how it works, how that engine fits together and how the components of it interact, this is what we need to do. So that's what we're doing.

[Finally], these are some pictures from my time at sea (Fig. 30).

Thank you very much.

Figure 29 'To be continued ...'

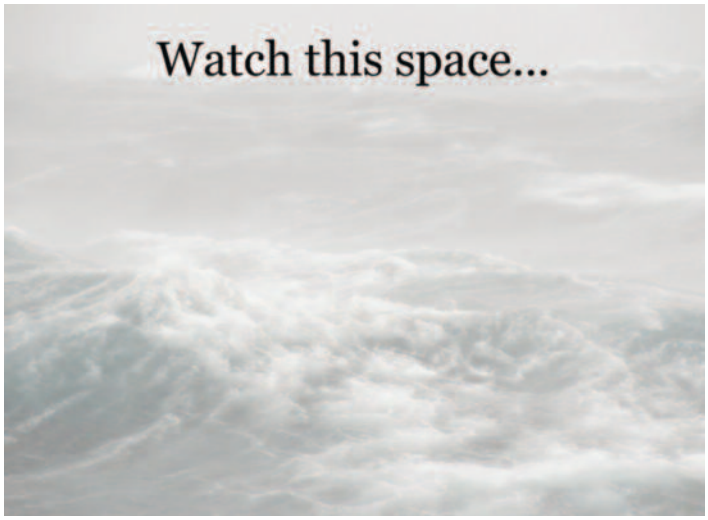
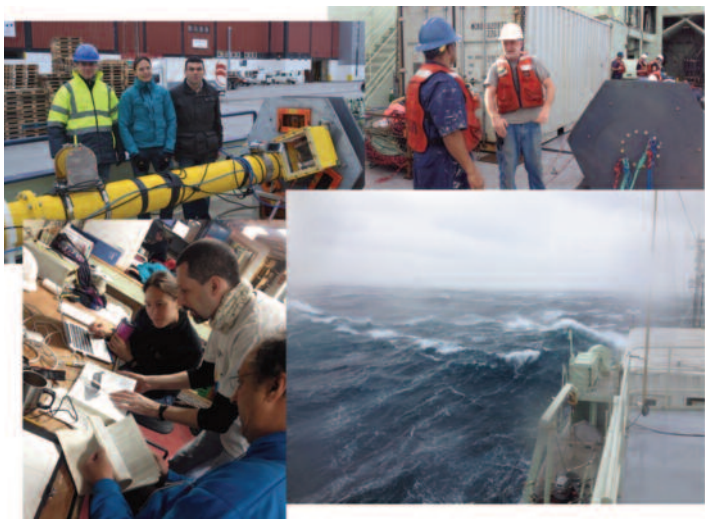


Figure 30 Time at sea.



Book review

Hiscock, Kevin M., and Bense, Victor F. 2014 *Hydrogeology: Principles and Practice* (2nd edn). Oxford: Wiley Blackwell (ISBN 978-0-47065-663-1; 504pp; paperback, £39.95)

Life is dependent on the availability of water. Fresh groundwater has been, and is the source of water for a large proportion of the world's population. Groundwater has been exploited by man for domestic and agricultural use since the beginning of civilisation. Today water is a major resource for domestic, agricultural and industrial uses. This book, made up of ten detailed chapters, draws on reservoirs, management and extraction practices around the world.

This is a detailed book, embracing global groundwater availability, reservoirs and aquifers; it is no bedtime reading, but is a serious study, analysis and interpretation of the subject matter. It is full of figures and tables and the student is guided by formulae, some of which may be challenging for the less mathematically minded. It is aimed at a global audience rather than at just British and European students and practitioners. It embraces the history of exploitation of groundwater and the project challenges we face in the future. From the hydrologic cycle, to discussions on porosity and permeability of the rocks beneath our feet, the book details the behaviour of different types of rocks as reservoirs and aquifers. Field methods for the practitioner are also discussed in detail. It draws inferences on agricultural use, particularly in geographic areas where there is imbalance in the the cycle.

As well as water being a necessity for life, contaminated groundwater can be a source of problems for users. Groundwater pollution has been a concern for the many, and most of the contamination is the result of historic as well as current human activity. The principal pollutants and their necessary remediation methods, as well as the necessary protection, are given prominence in the book. Water is also a finite resource, especially in areas where there is imbalance in the hydrological cycles, and replenishment through precipitation is a challenge. An interdisciplinary book, it will not disappoint the environmentalists, as it covers in detail the legal framework governing extraction, contamination and remediation of groundwater. It also analyses the various contaminants and discusses their possible treatment.

Sandwiched in the middle are 16 pages of plates, colour pictures mainly, of ground penetrating, distribution and exploitation of groundwater reserves and other useful information — e.g. recharge tables around the globe. It also gives insight into earlier extraction methods, with pictures of now defunct village pumps.

A useful resource for the student of hydrogeology, it is also a handy book for the environmentalist and a practical book for practitioners all over the world.

— Kwame Ofori BA Hons

What lies beneath: offshore data acquisition and how we turn those data into science

Heather A. Stewart

(British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA)
(hast@bgs.ac.uk)

Abstract

Detailed and accurate mapping of the marine environment is important for a number of stakeholder groups, including energy companies (oil and gas, and, increasingly, offshore renewables), policy groups who require environmental data for marine spatial planning, resource and conservation management, and academic researchers who aim to better understand the processes that initially formed, and continue to shape these environments.

Since the 1960s both industry and researchers alike have undertaken systematic exploration of the UK offshore territory (e.g. Gatliff et al. *1994; Johnson* et al. *1993; Ritchie* et al. *2011 and references therein). More than 11,000 industry exploration and production wells, and 580 scientific boreholes have been acquired in UK waters. Other physical sampling techniques such as Shipek Grabs that sample the seabed sediments, vibrocorers, gravity corers, piston corers and rock corers total more than 45,000 samples in the territorial waters of the United Kingdom (UK). Integration of these physical samples with 2D and 3D seismic reflection data, and with multibeam echosounder data facilitate the production of detailed maps and an improved understanding of our offshore area. International programmes such as the International Ocean Discovery Program, are also a means by which researchers can acquire offshore data.*

This paper briefly summarises both traditional techniques and the development of newer tools for offshore data acquisition. Case studies from the central North Sea and offshore deep-water areas of the UK are presented to illustrate their application.

Introduction

Land-based geological mapping and exploration has been ongoing for hundreds of years, on every continent on Earth, and has been one of the core activities of the British Geological Survey (BGS) since 1835 (Fig. 1). Yet, it is unwise for any nation to ignore its offshore domain, particularly since the United Nations Law of the Sea Conference in 1958 allowed coastal nations to exploit the natural resources of their sectors of the continental shelf out to 200 miles. Offshore territory has huge economic and environmental potential, especially to an island nation like the UK where the offshore area is about three times its land area (Fig. 2).

Figure 1 Group photograph of the Geological Survey of Scotland, Inchnadamph, north-west Highlands 1889: back row left to right J. Horne, L. W. Hinxman, W. Gunn, J. Linn; front row left to right G. Barrow, B. N. Peach and J. B. Hill; seated front left J. Dakyns.

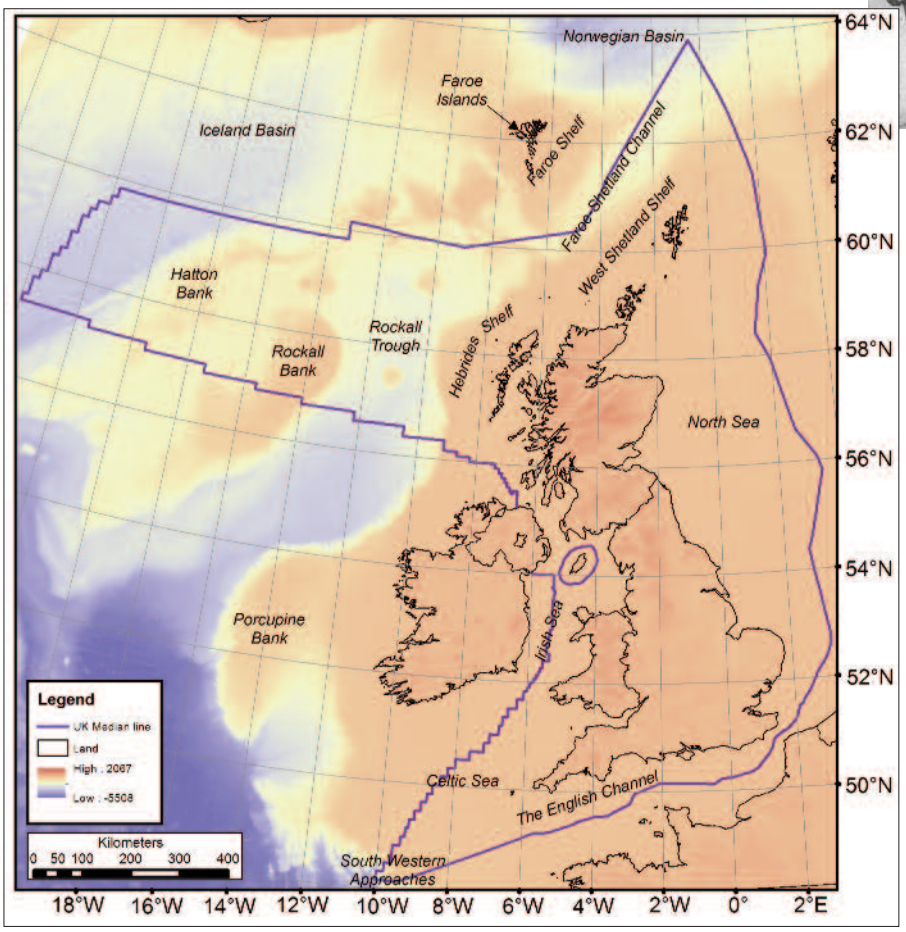


Figure 2 The offshore territorial waters for the United Kingdom delineated by the purple median line. Generalised topography of the seabed has been derived from GEBCO (www.gebco.net).

The early days

By the 1850s ships had been routinely crossing the Earth's oceans for 200 years. Although the coastlines of the main landmasses had been surveyed, little was known about the sea beyond a few tens of metres water depth. As the 19th century progressed there was increasing pressure to explore the ocean depths for both scientific

© OUGS ISSN 2058-5209

Figure 3 Crew and scientists of the RRS Challenger 1872.

purposes and for commercial reasons. For example, laying cables for communication between Europe and America by telegraph could only be successfully achieved through improved knowledge of the shape and composition of the sea floor.

One of the earliest offshore scientific expeditions, the Challenger Expedition of 1872–1876 (Fig. 3), covered nearly 70,000 nautical miles, acquired soundings for water depth, and collected seafloor, water and biological samples. In 1895 Sir John Murray, who supervised publication of the scientific results from the expedition, described the scientific work conducted as "the greatest advance in the knowledge of our planet since the celebrated discoveries of the fifteenth and sixteenth centuries".

Originally, geological exploration of the oceans would have involved measurement of water depths using pre-measured heavy rope or cable. Often the cable or rope had a bucket or dredge attached to the end in the hope of collecting a sample of the sea floor while recovering a 'sounding' or point water depth. This was certainly the method employed by the scientists on board *RRS Challenge*r and many of the other ground-breaking expeditions of that era. In the first half of the 20th century, the lead-line method was gradually replaced by the newly invented single-beam echosounder to ascertain water depth. The amount of time taken for a 'ping' — a beam of sound — to travel from the source through the water column, bounce off the sea floor and return to the sounder gave a distance between the sounder and the sea floor. These point water depths were plotted on charts (Fig. 4A) primarily produced for navigation, but were also utilised by scientists.

One of the most famous world maps is that of Heezen and Tharp (1977). The 1977 map was a revelation and showed the main plate boundaries as delineated by giant mountain chains at convergent and constructive margins, and oceanic trenches at subduction zones. At this time, the relatively new theory of plate tectonics was a contentious subject yet to gain momentum and support. It is astounding to realise that their ground-breaking

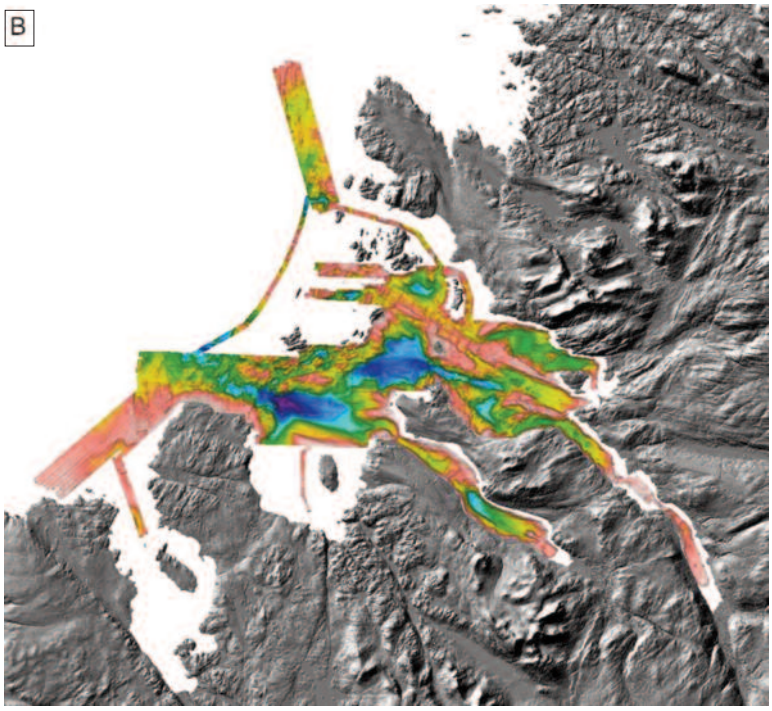


Figure 4 (A) The Loch Inver to Loch Broom Admiralty Chart published in 1857 by the Hydrographic Office of the Admiralty. The soundings are in fathoms rather than metres. (B) Multibeam bathymetry data acquired by the BGS covering a large part of the 1857 chart, but showing the seabed in great detail, including moraines marking the limits of former ice sheets, and mega-scale glacial lineations that indicate the direction of ice expansion (terrestrial topographic data are derived from Intermap Technologies NEXTMap Britain elevation data).

work was based on point water depth data and represented the first systematic attempt to map the entire ocean floor.

Today, multibeam echosounders are routinely used to measure water depths. As the name suggests, multibeam echosounders (Fig. 5) emit hundreds of beams of sound in a swath, which therefore covers more of the seabed, is faster than earlier methods, and gives higher precision and confidence in the accuracy of the data being collected. Once these data have been corrected for a number of variables such as vessel movement on the sea surface and the influence of tides and position, a digital terrain model can be generated that shows the topography of the sea floor in more detail than ever before (Figs 4B, *opposite*, and 6).

Knowing the shape of the seabed alone is not enough to understand the formation, composition and setting of a given area. Data giving information on the sub-surface are required — what lies under the seabed? Once again, sound was part of the answer, as the sub-seabed is penetrated by a controlled source of energy. In the early days dynamite or oxyacetylene (gas explosions!)

Figure 5 Mounting of the sonar heads of an EM3002D multibeam echosounder using the moon pool located in the hull of the BGS 9m catamaran survey vessel White Ribbon.

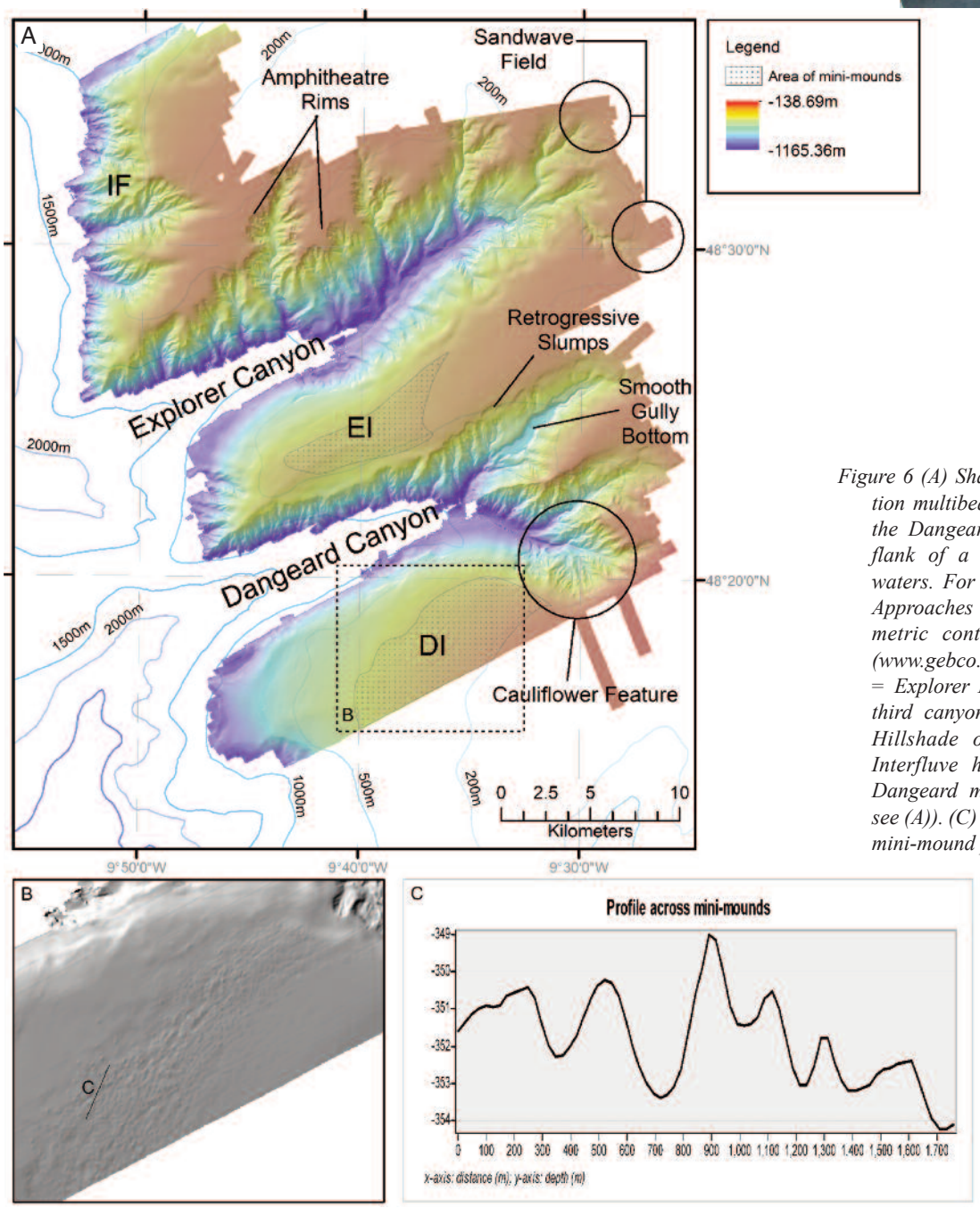


Figure 6 (A) Shaded relief map of the high-resolution multibeam bathymetry data acquired over the Dangeard and Explorer canyons and the flank of a third canyon in Irish territorial waters. For the location of the South Western Approaches see Figure 2 (generalised bathymetric contours are derived from GEBCO (www.gebco.net). DI = Dangeard Interfluve, EI = Explorer Interfluve, IF = eastern flank of a third canyon in Irish territorial waters). (B) Hillshade of the topography of Dangeard Interfluve highlighting the presence of the Dangeard mini-mound province (for location see (A)). (C) Profile across part of the Dangeard mini-mound province (for location see (B)).

was used as the energy source, but today compressed air being released by an airgun or mini-gun, or different electrical sources are primarily used. These data are collectively known as seismic data.

The depth below the seabed that can be imaged is dependent on the power and type of energy source used. These can be split into three main windows:

- from the seabed down to *c*. 1km below the seabed, such as used for geotechnical and environmental studies — and more recently also for carbon capture and sequestration and geothermal energy;
- up to 10km below the seabed, such as used for hydrocarbon exploration and for carbon capture and sequestration; and
- crustal studies at depths of up to 100km below the seabed for studies into the structure and origin of the Earth's crust.

With the advent of digital seismic-data recording in 1965, there was a steady, year-on-year increase in the volume of 2D seismic data acquired in UK territorial waters (Fig. 7A), largely driven by the search for oil and gas. 2D seismic acquisition peaked in the 1980s following the rise in oil price and gradually began to fall in the late 1980s as these 2D slices through the seabed were replaced by the acquisition of 3D seismic cubes (Fig. 7B). The first 3D seismic surveys were acquired in the late 1970s and were generally accepted by the 1990s as a necessity for hydrocarbon field delineation and development. The North Sea is considered to be a mature province in terms of oil and gas exploration, but new discoveries are still being made today. More recently both 2D and 3D seismic data have been used for scientific research rather than only for hydrocarbon exploration and exploitation, for example looking at the sequences of glacial and interglacial events in the North Sea

Figure 7 (A) Example of 2D Sparker seismic line acquired by the BGS in 1985: purple and green lines = boundaries between seismostratigraphic packages; red and blue lines = the base of tunnel valley features that form under ice sheets. (B) Example of 3D seismic cube from the central North Sea showing tunnel valleys (outlined in colours to show phases of tunnel valley formation) in time-slice at 281ms and in cross section: the horizontal resolution of the volume is 12.5m; cross-cutting relationships are apparent between a number of tunnel valleys (after Stewart et al. *2013).*

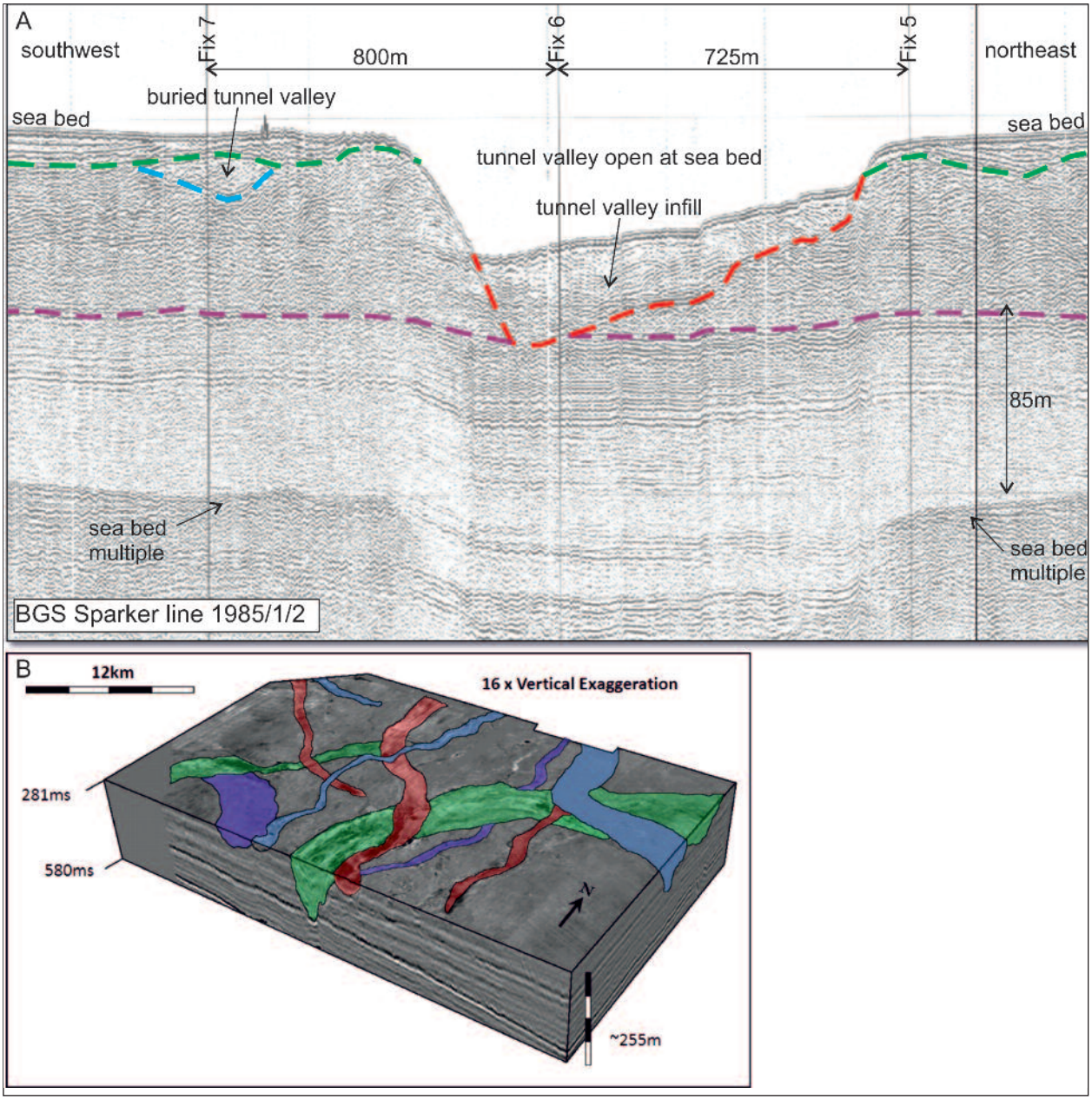


Figure 8 (A) BGS divers preparing for work at Burnmouth, Berwickshire 1968: left to right R. A. Eden, J. Davidson and A. Chambers. (B) BGS diver sampling the seabed offshore Lossiemouth, Moray, Scotland.

and their associated sediments and glacial landforms (Fig. 7; e.g. Graham *et al*. 2011; Praeg 2003; Stewart *et al.* 2013).

In conjunction with the seismic data, the ideal situation is to collect physical samples of the rocks underlying the seabed to 'ground-truth' the seismic data. Actual samples are the only way to accurately identify the changes in lithology that form the various reflectors observed on the seismic data. The methods for acquiring samples from the ocean depths vary from a bucket or dredge on the end of a cable, to diver surveys (Fig. 8), to remotely operated seabed rock drills and vibrocorers (Fig. 9), to complex operations using drill ships (Fig. 10, *overleaf*) and platforms.

The BGS designed and built their first remotely operated rock drill in the late 1960s. *CONSUB* was a remotely operated vehicle (ROV) capable of retrieving short cores from the seabed. It was only operational for a relatively short time and was decommissioned in the early 1970s to be replaced by a seabed rock drill. The midi-drill was operational between 1975 and 1983 and was capable of collecting cores up to 1m long. The midi-drill was constrained to shallower water depths, and as scientific exploration moved into deeper water a new version of the rock drill (RD1) was designed and built in-house. RD1 has been in operation since 1982 and is still in use today. Capable of acquiring

Figure 9 (A) The BGS 55m remotely operated seabed rock drill (RD2) being deployed in the Sea of Japan. (B) The BGS 6m vibrocorer being deployed from the stern of the RRS James Clark Ross *during joint operations between the BGS and the British Antarctic Survey. The Larsen Ice Shelf is visible in the background.*

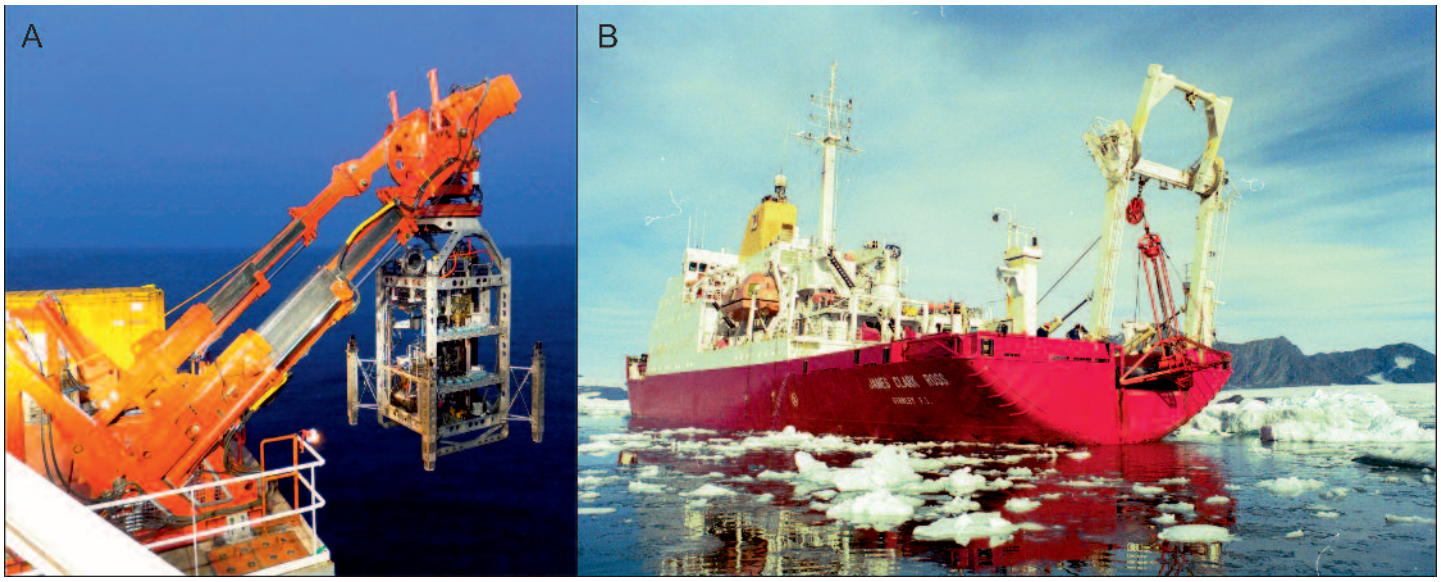


Figure 10 (A) IODP Tahiti Sea Level Expedition 310: scientists having an active discussion in the core curation laboratory offshore (photo by M. Koelling © ECORD/IODP). (B) IODP Arctic Coring Expedition 302: the drill vessel Vidar Viking *operating in 90% multi-year ice drilling the Lomonosov Ridge, Arctic Ocean (photo by M. Jakobsson © ECORD/IODP).*

cores up to 5m long, this drill has been deployed all over the world from the Rockall Trough offshore western UK, to Antarctica and Papua New Guinea. In abyssal water depths (>2,000m water depth) the BGS vibrocorers (Fig. 9B) have been modified to operate using new battery technology (operational water depth now 6,000m), and an Oriented Drill was designed for palaeomagnetic research at mid-ocean ridges (at 5,100m water depth). The newest BGS rock drill (RD2; Fig. 9A) is capable of coring up to 55m sub-seabed in 4,000m of water.

The longest-running scientific drilling effort is the International Ocean Discovery Program and its precursors. In 1957 a proposal to drill to the Mohorovičić discontinuity was submitted to the National Science Foundation of the United States of America. Drilling was not attempted until 1961 when, in the Gulf of Mexico, 200m of sediment and 14m of basalt were cored as part of project MOHOLE. That feat was only possible with the invention of dynamic positioning, the method by which a vessel can hold position on a specific site for a long period.

By 1964 an ocean drilling consortium called JOIDES (Joint Oceanographic Institutions for Deep Earth Sampling) had been formed, committed to setting up a framework whereby international scientists could propose scientific sites to core in order to further scientific understanding utilising a custom-built drillship. In 1968 the *Glomar Challenger* set sail on the first Deep Sea Drilling Project (DSDP) cruise and over the next 18 years DSDP expeditions proved the theory of sea-floor spreading (Leg 3) and sampled the Mariana Trench (Leg 60), the deepest place in the ocean.

In 1985 the *JOIDES Resolution* set sail on Leg 100, signalling the next phase of scientific drilling as part of the Ocean Drilling Program (ODP). From 1985 until 2003 the ODP sampled the oldest oceanic crust (Jurassic in age) in the north-west Pacific Ocean (Leg 129) and documented abrupt climate change during the Paleocene/Eocene Thermal Maximum and Eocene hyperthermals in the Pacific Ocean (Legs 198 and 199).

The *JOIDES Resolution* continued in service as part of the Integrated Ocean Drilling Program (2003–2013) and is still operating as part of the current International Ocean Discovery Program (2013–2023). The *JOIDES Resolution* was joined by the Japanese research vessel *Chikyu* in 2007, the first riser-equipped drilling vessel specifically built for science; and by Mission Specific Platforms (MSPs) in 2004, which provide drilling platforms to meet specific scientific challenges that cannot be sampled by either the *JOIDES Resolution* or the *Chikyu*. MSPs have enabled the drilling of previously inaccessible locations for science, such as the shallow waters around Tahiti (Exp 310; Fig. 10A), and the ice-covered waters of the Arctic Ocean (Exp 302; Fig. 10B).

Exploring the Dangeard and Explorer Canyons — dramatic seascapes and biological refuges

Pressure on the marine environment is growing through fishing methods such as bottom-trawling, climate change, ocean acidification and, more recently, deep-sea mining. Establishing a representative network of Marine Protected Areas (MPAs) and Marine Conservation Zones (MCZs) offers a tool with which to address conservation needs. A number of international, European and national policies contribute to the planning and delivery of these conservation areas. The following policies are key:

- United Nations General Assembly resolution 61/105
- Habitats Directive (92/43/EEC)
- OSPAR Convention (2008)
- Marine Strategy Framework Directive (Directive 2008/56/EC)
- Convention on Biodiversity 'Strategic Plan for Biodiversity 2011–2020'
- Marine and Coastal Access Act (2009)
- The Marine (Scotland) Act (2010)

Maps have proved to be a useful method of summarising both geological and biological information concerning the seabed, facilitating marine spatial planning and enabling the assessment of progress towards conservation targets.

Topographic features such as canyons, large-scale features that are incised into the continental shelf break, have been described as 'biodiversity hotspots' (Schlacher *et al.* 2007), yet there are few studies of these features. In a new assessment of submarine canyons, researchers estimate that the area of the sea floor covered by canyons is 1.2% of the total ocean area, *c*. 4.4 million km^2 (Harris *et al.* 2014). The complex terrain and diverse range of seabed habitats play a part in submarine canyons being

described as areas of high habitat heterogeneity (Schlacher *et al.* 2007). In other words canyons are home to a wide range of sediments, from muds to sand and gravel, as well as areas of rock cropping out at seabed. Canyons also host a diverse range of organisms that live both on the seabed and within the sediments, and, of course, species that swim in the water column.

Within the waters of the UK, canyons only incise the continental shelf in one area: the South Western Approaches (for location *see* Fig. 2). In order to assess potential conservation needs, the heads of Dangeard and Explorer canyons were surveyed during a MESH (Mapping European Seabed Habitats) cruise on board the *R/V Celtic Explorer* in 2007 (*see* Fig. 6A; Stewart *et al.* 2007). The Dangeard and Explorer canyons comprise a dendritic network of gullies feeding into two main canyons (*see* Fig. 6a; Stewart *et al.* 2014). High slope angles (>20°) were observed in the heads of both canyons and are indicative of mass-wasting processes resulting in transport of sediment down the canyon and erosion backward into the continental shelf (Stewart *et al.* 2014).

Not only did the acquisition of multibeam echosounder data enable visualisation of the shape, or morphology of these canyons (as shown in Fig. 6), but it also revealed something unexpected. More than 400 'mini-mound' features were identified on the un-dissected areas of continental shelf in between the Dangeard and Explorer canyons (*see* Fig. 6A and B). These mounds are up to 3m in height and between 50m and 150m in diameter, and are made of cold-water coral rubble that was once living coral reef, but has since been damaged (*see* Figs 6C and 11A and B; Davies *et al.* 2014; Stewart *et al.* 2014). In addition, cold-water coral reefs, formed predominantly by the coral *Lophelia pertusa* with lesser occurrences of the coral *Madrepora oculata* (Fig. 11C), were observed on the canyon flanks. Anthropogenic debris associated with fishing activity was also observed in a third of video transects (Fig. 11D; Stewart and Davies 2007) and starkly illustrates the impact some human activities are having on the marine environment.

The acquisition of multibeam echosounder data, combined with video ground-truthing data and 2D seismic data, has provided a better understanding of the origin, evolution and biological assemblages of the hitherto poorly studied submarine canyons and mini-mounds in the UK offshore area. Of particular interest

*Figure 11 (A) Example photograph of typical reef rubble habitat comprising abundant coral fragments observed on the mini-mound features on the smooth tops in between the incised canyons. (B) Example photograph of seabed observed between the mini-mounds. (C) Example photograph of cold-water coral reef (*Lophelia pertusa*) observed on the flanks of Explorer and Dangeard canyons (exact size of the field of view is unknown). (D) Example photograph showing the sort of debris observed left behind by humans: this net was observed 'ghost fishing' in the canyons (exact size of the field of view is unknown).*

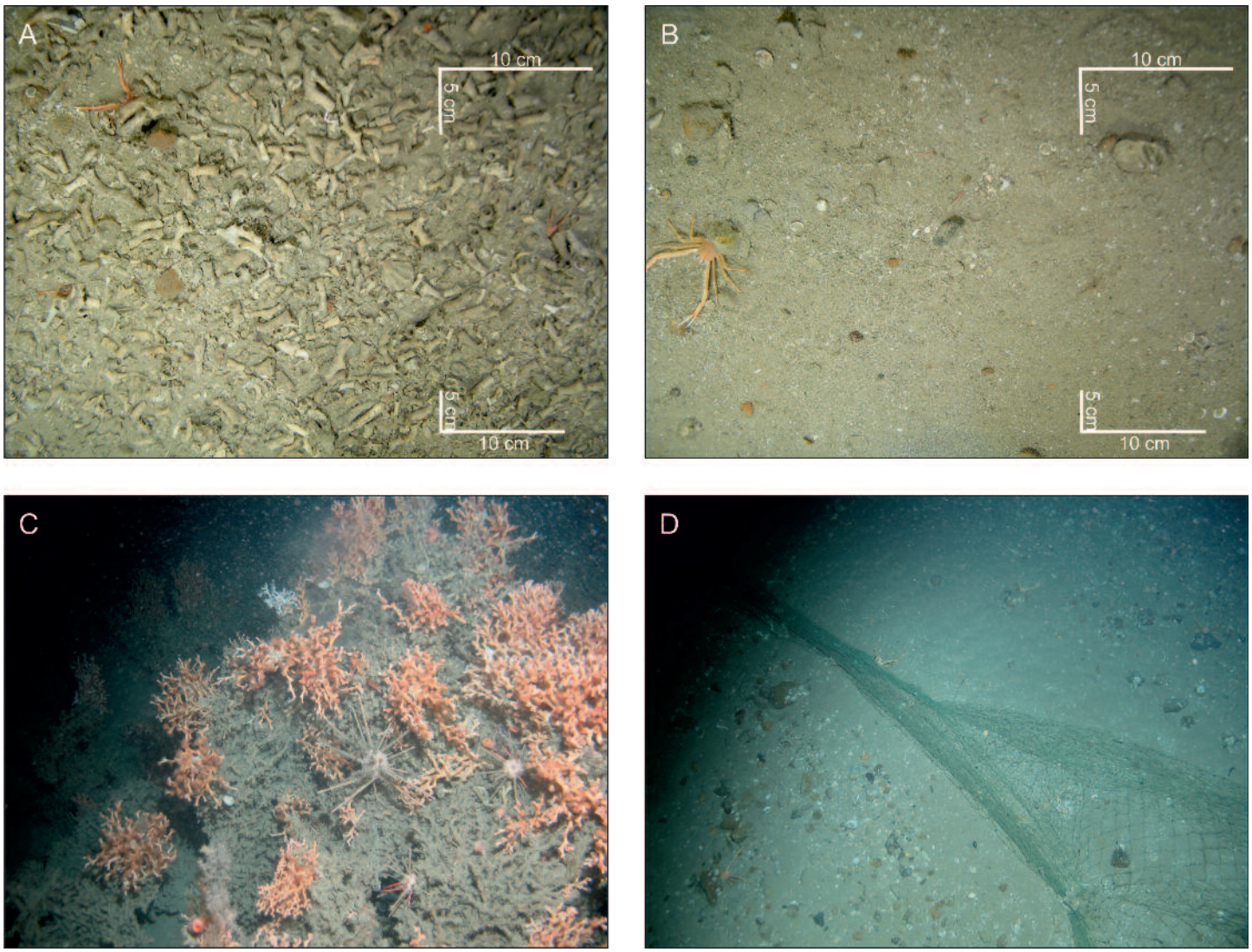
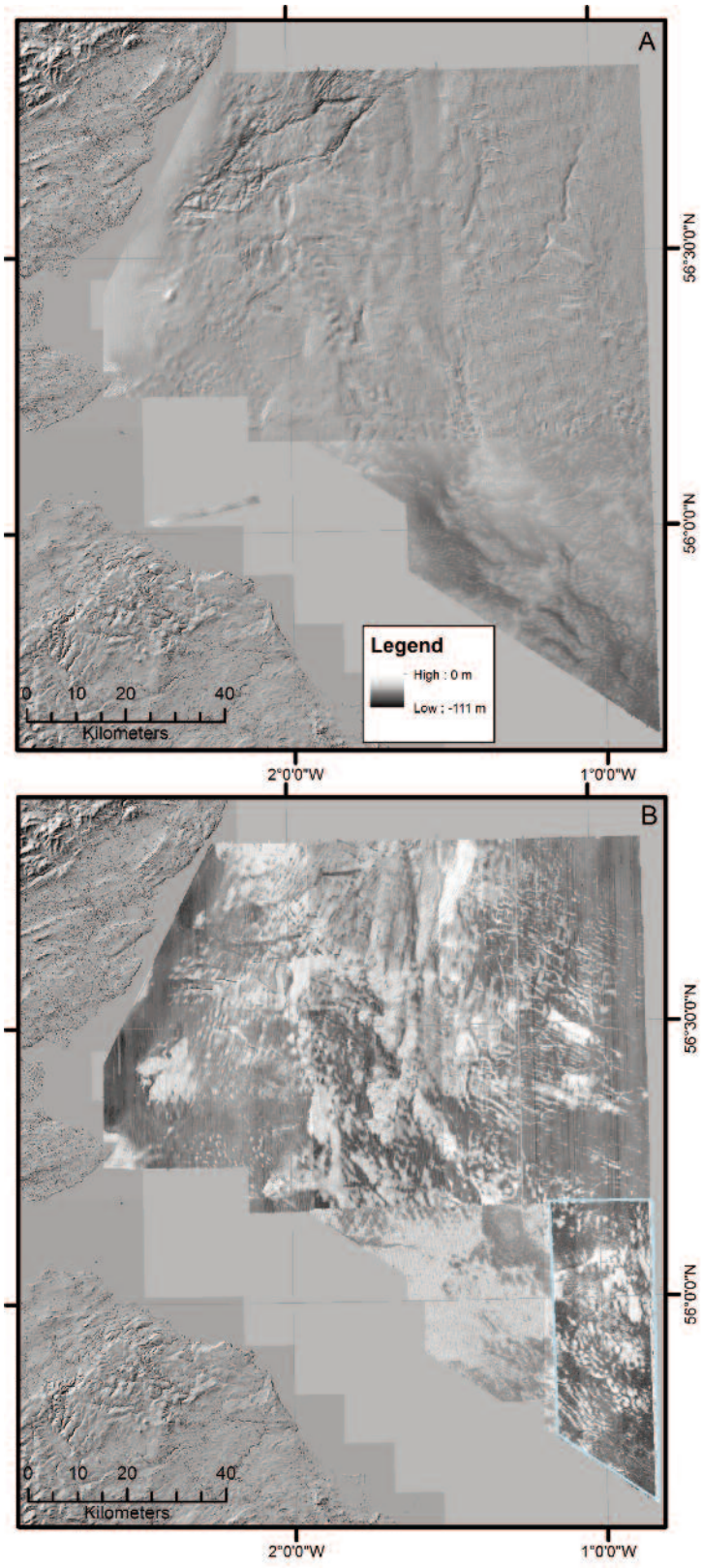


Figure 12 (A) Shaded relief map of the high-resolution multibeam bathymetry data acquired offshore eastern Scotland by the Marine and Coastguard Agency. (B) Overview of the backscatter intensity data available in the study area. Note that the backscatter intensity data have been processed in subsets to optimise the data quality for each area (terrestrial topographic data shown in (A) and (B) is derived from Intermap Technologies NEXTMap Britain elevation data).



was the discovery of biological communities of conservation concern, which led to the canyons being proposed and subsequently included in the UK Marine Conservation Zone network (The Canyons MCZ) in November 2013.

Drumlins in the deep — glacial geomorphology in the central North Sea

Multibeam echsounder data acquired by the Maritime and Coastguard Agency in the western North Sea have been used to map geomorphological features associated with the Strathmore, Forth–Tay and Tweed palaeo-ice streams (Fig. 12). It is likely that these features, preserved on the seabed, are evidence of the most recent phase of glaciation, when ice expanded out over the continental shelf at the Last Glacial Maximum. In this case study, digital terrain models derived from the multibeam bathymetry (Fig. 12A) were used for geomorphological mapping in conjunction with the backscatter intensity data (Fig. 12B) that is often overlooked. Backscatter intensity data are acquired simultaneously with the bathymetric soundings. The strength of the backscattering is dependent upon sediment type, grain size, survey conditions, seabed roughness, compaction and slope.

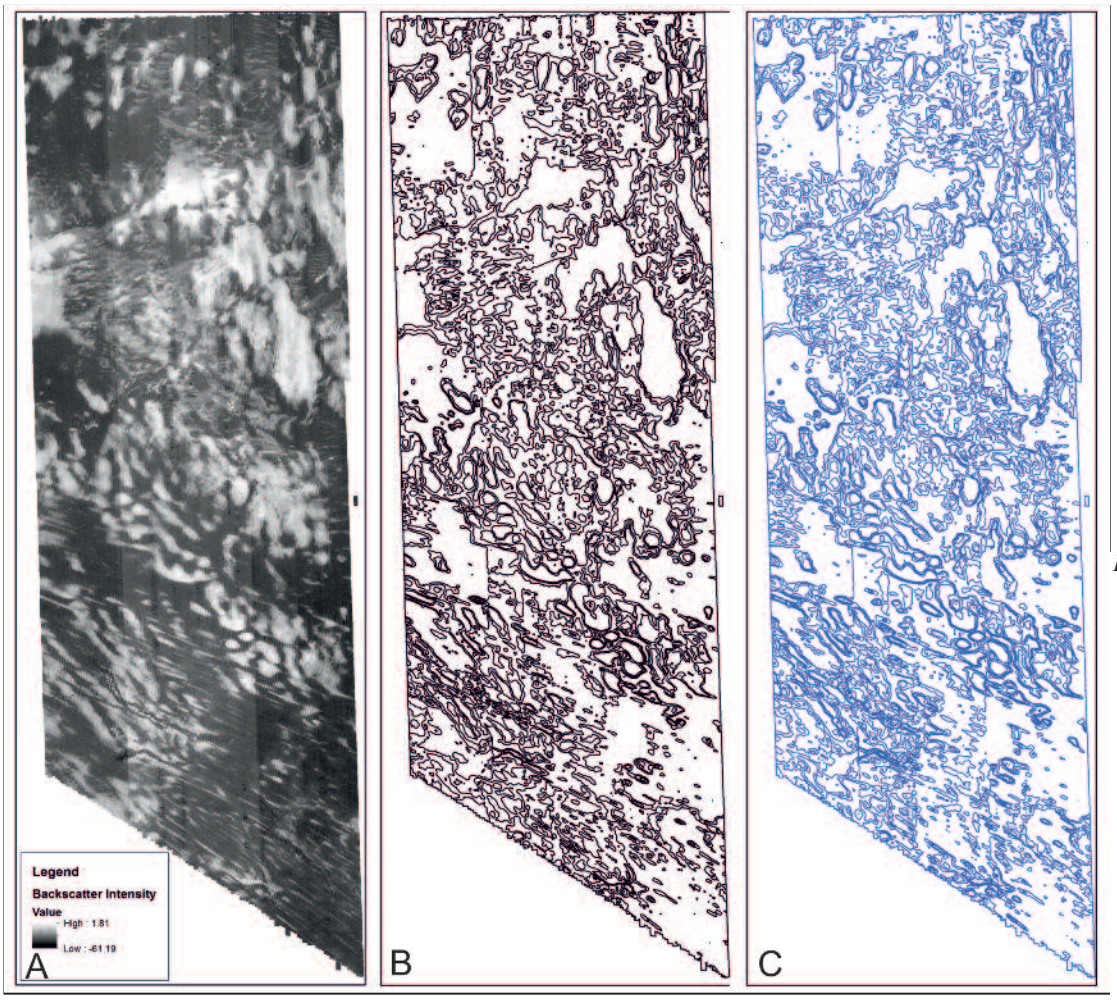
The BGS generated backscatter intensity maps using FM Geocoder, and then gridded these data at the best resolution per dataset (between 2m and 5m). In the study area BGS next undertook a combination of semi-automated classification of the backscatter intensity data (a predictive method for mapping variations in surficial seabed sediments) and manual interpretation (Fig. 13, *opposite*).

Four separate drumlin fields have been mapped in the study area, indicative of fast-flowing and persistent ice-sheet flow configurations. A number of individual drumlins were also identified, located outside the fields. The drumlins show as areas of high backscatter intensity compared to the surrounding seabed, indicating the drumlins comprise mixed sediments of gravelly sands and sandy gravels compared to the surrounding sandy and muddy sediments (Fig. 14, *page 32*).

The combination of semi-automation and expert judgement used for the interpretation of both seabed sediments and geomorphology has been shown to produce a robust glacial geomorphological map. This technique is very effective where glacial sediments have been deposited in areas of softer bed sediments, resulting in the juxtaposition of different backscatter intensity values. The technique is not as effective in areas of bedrock or over-consolidated sediments, where the backscatter intensity value varies little between the moulded/deposited glacial features and the surrounding seabed.

Concluding Remarks

There is international momentum for the systematic mapping of the sea floor with several major programmes in place, e.g. MAREMAP (UK), MAREANO (Norway) and the Irish National Seabed Survey (Republic of Ireland). At a European level, maps of the sea floor are being compiled by geological organisations involved in the EC-funded European Marine Observation and Data Network (EMODnet). Maps enable managers and politicians to manage offshore resources such as renewable energy and conventional hydrocarbons, sites for carbon capture and sequestration, and aggregates. Maps also make



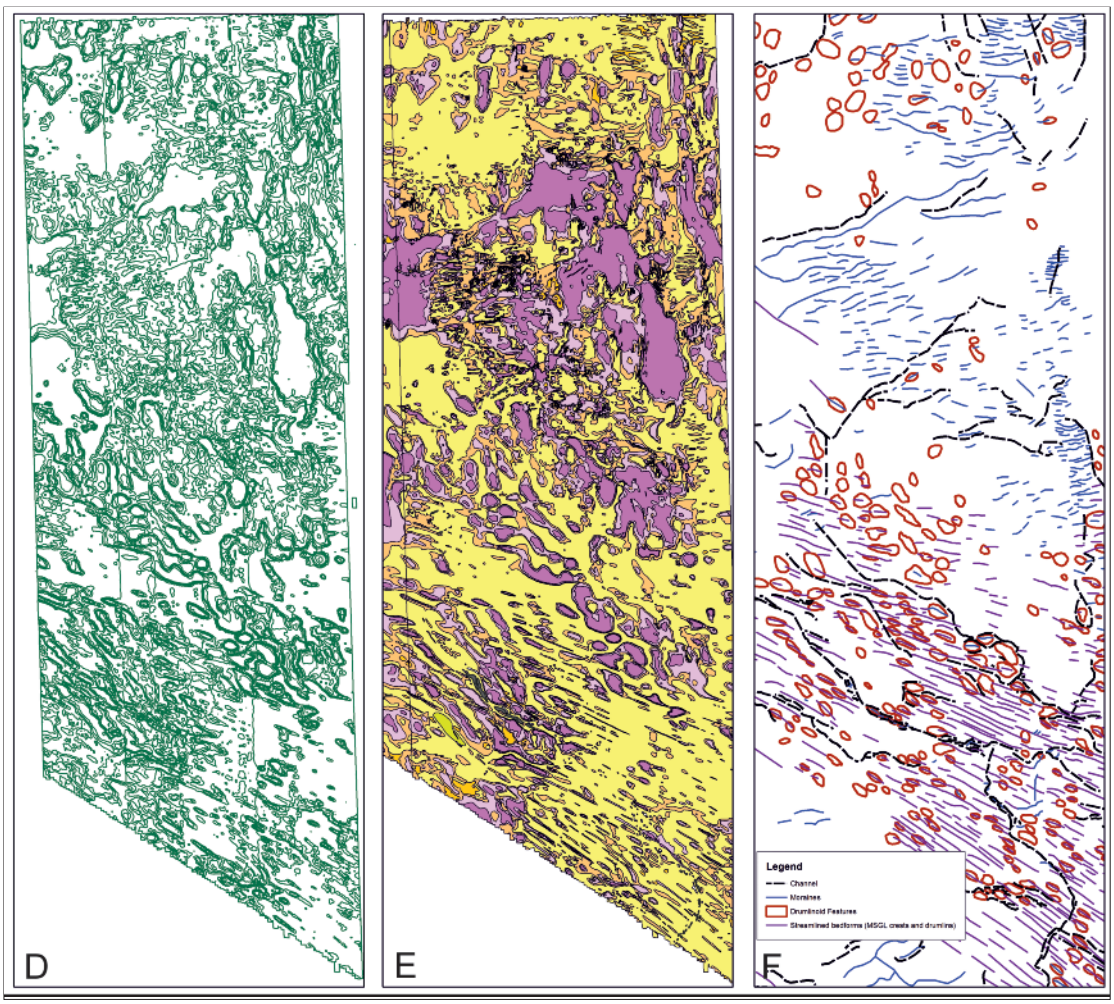
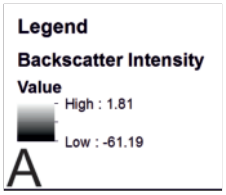


Figure 13 (A) Example of processed backscatter intensity data at 2m resolution (for location see Figure 12). Polygons generated using the semi-automated method with 4 classes (B), 5 classes (C), and 6 classes (D). (E) Resultant seabed sediment interpretation over the area of interest. (F) Interpretation of the glacial geomorphology preserved on the seabed (for location see blue outline on Figure 12B).



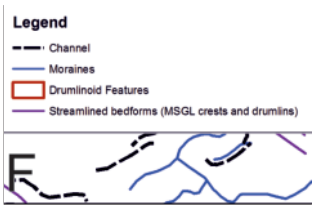
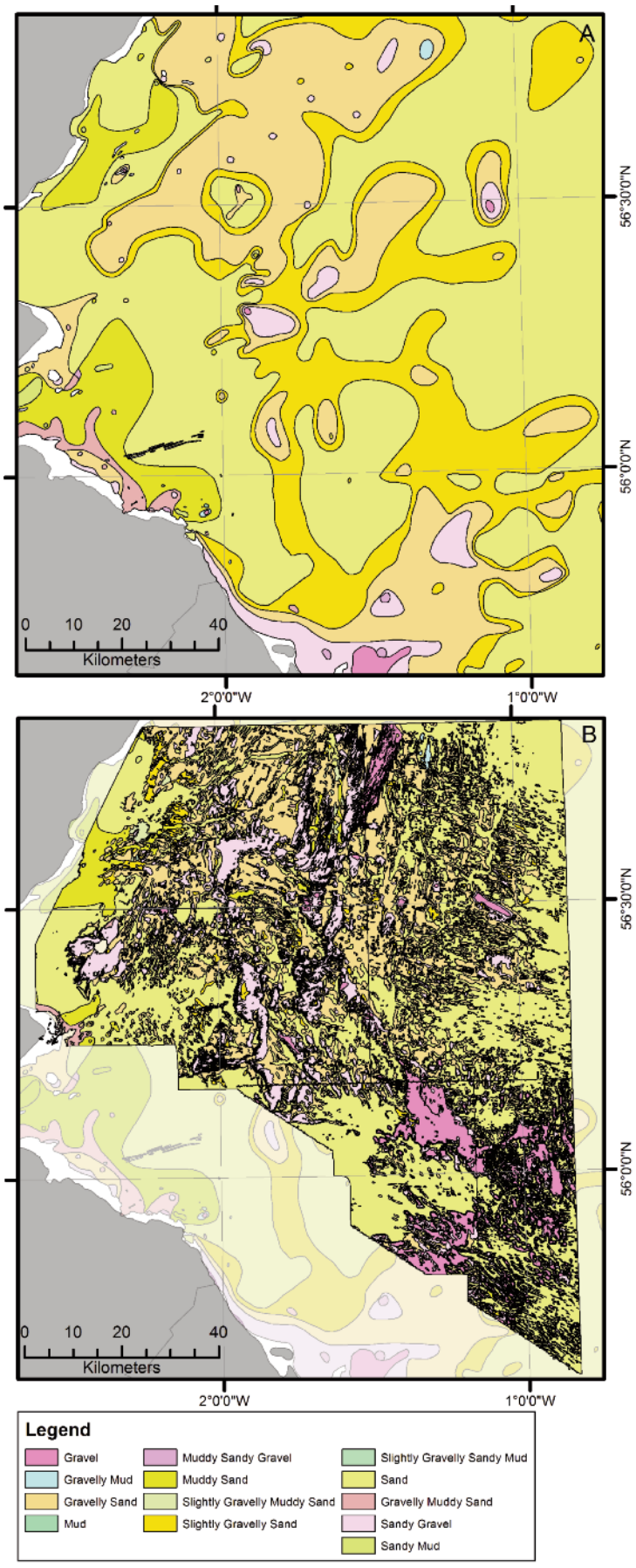


Figure 14 (A) The previous seabed sediment interpretation (mapping scale of 1:250,000) for the study area located offshore eastern Scotland. (B) The updated seabed sediment interpretation (new mapping scale of 1:50,000) that made use of recently available multibeam bathymetry and backscatter intensity data.



it possible for marine spatial planners to design and implement conservation networks in order to preserve our biologically and geologically diverse marine-scapes and to safeguard our archaeological inheritance.

The production of scientifically robust maps and models can only be undertaken if scientists use all available interpretation tools.

"Probably the greatest enticement for those who today are devoting their lives to the study of the sea is the lure of the unknown, the challenge of the undiscovered, the thrill of discovery on what is truly the last frontier on earth." (Stewart 1966, 7)

Acknowledgements

The author wishes to thank the captain, crew and science parties of the many offshore expeditions summarised in this article.

All images ©BGS/NERC with the exceptions of:

Figure 4 UK Hydrogrpahic Office ©Crown copyright;
Figures 6 and 11 Joint ©2007 Defra, JNCC, Marine Institute, British Geological Survey and University of Plymouth;
Figure 10a M. Koelling ©ECORD/IODP;
Figure 10b M. Jakobsson ©ECORD/IODP; and
Figures 12 and 13a multibeam echosounder data provided courtesy of the Maritime and Coastguard Agency's UK Civil Hydrography Programme ©Crown copyright.
R. Cooper processed the backscatter intensity data presented in the *Drumlins in the Deep* case study and undertook all polygon generation via the semi-automated classification of the backscatter intensity data (Figures 12b and 13).
A. Stevenson is thanked for his comments on an earlier version of the manuscript.
The author publishes with permission of the Director, British Geological Survey (Natural Environment Research Council).

References

Davies, J. S., Howell, K. L., Stewart, H. A., Guinan, J., and Golding, N. 2014 'Defining biological assemblages (biotopes) of conservation interest in the submarine canyons of the South West Approaches (offshore United Kingdom) for use in marine habitat mapping'. *Deep-Sea Research* **II** 104, 208–29

Gatliff, R. W., Richards, P. C. *et al.* 1994 *United Kingdom Offshore Regional Report: the Geology of the Central North Sea*. London: HMSO, for the British Geological Survey

Graham, A., Stoker, M. S., Lonergan, L., Bradwell, T., Stewart, M. 2011 'The Pleistocene glaciations of the North Sea Basin', *in* Ehlers, J., Gibbard, P. L., Hughes, P. D. (eds), *Quaternary Glaciations: Extent and Chronology: a Closer Look*. Developments in Quaternary Science, vol. 15. London: Elsevier, 261–78

Harris, P. T., MacMillan-Lawler, M., Rupp, J., Baker, E. K. 2014 'Geomorphology of the oceans'. *Marine Geol* **352**, 4–24

Heezen, B., and Tharp, M. 1977 'World Ocean Floor Panorama'. Copyright by Marie Tharp 1977/2003. www.marietharp.com

Johnson, H., Richards, P. C., Long, D., and Graham, C. C. 1993 *United Kingdom Offshore Regional Report: the Geology of the Northern North Sea*. London: HMSO, for the British Geological Survey

OSPAR (Agreement 2008–6). OSPAR Agreement 2008–6 that replaced an earlier version of the list contained in OSPAR Agreement 2004–6 (see also the Summary Record of the 2008 meeting of the OSPAR Commission contained in OSPAR 08/24/1, Para. 7.12)

Praeg, D. 2003 'Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea Basin—high resolution from low frequencies'. *J Applied Geophys* **53**, 273–98

Ritchie J. D., Ziska H., Johnson H., and Evans D. 2011 *Geology of the Faroe–Shetland Basin and Adjacent Areas.* British Geological Survey Res Rep **RR/11/01**, Jarðfeingi Res Rep **RR/11/01**. London: HMSO, for the British Geological Survey

Schlacher, T. A., Schlacher-Hoenlinger, M. A., Williams, A., Althaus, F., Hooper, J. N. A., Kloser, R. 2007 'Richness and distribution of sponge megabenthos in continental margin canyons off southeastern Australia'. *Marine Ecology Progress Series* **340**, 73–88

Stewart, H. A., and Davies, J. S. 2007 *SW Approaches MESH Survey, R/V Celtic Explorer Cruise CE0705, BGS Project 07/06, Operations Repor*t. British Geological Survey Commercial Report **CR/07/123**

Stewart, H. A., Davies, J. S., Guinan, J. C., and Howell, K. L. 2014 'The Dangeard and Explorer Canyons, South Western Approaches UK: Geology, sedimentology and newly discovered cold-water coral mini-mounds'. *Deep-Sea Research* **II** 104, 230–44

Stewart, H. B. 1966 *Deep Challenge*. New York: Van Nostrand

Stewart, M. A., Lonergan, L., and Hampson, G. 2013 '3D seismic analysis of buried tunnel valleys in the central North Sea: morphology, cross-cutting generations and glacial history'. *Quaternary Sci Rev* **72**, 1–17

Useful Links

www.bgs.ac.uk/research/marine
www.iodp.org
www.eso-ecord.org
www.maremap.ac.uk
Twitter: @BGSMarineGeo; @BritGeoSurvey

Book review

Ridley, John 2013 *Ore Deposit Geology*. Cambridge University Press (978-1-10702-222-5; hardback, xi + 398pp; £40)

First, a caveat: I approached this book as a student who wanted to learn more about ore deposits rather than as an expert on ore deposits. I learned a lot and discovered many fascinating facts. Were you aware, for example, that the Sudbury Igneous Complex in Canada is an astrobleme, a meteorite impact site? Or that diamantiferous kimberlite pipes are much, much younger than their host rocks?

There are a lot of things I liked about this book. Its layout is well ordered and clear. Chapter 1 'What is an ore deposit?', Chapter 2 'Magmatic Ore Deposits', Chapters 3 and 4 are devoted to 'Hydrothermal Ore Deposits', Chapter 5 covers 'Ore Deposits formed in Sedimentary Environments', and, finally, Chapter 6 covers 'Supergene Ores.' There is an excellent Glossary on pp357–68 and my first incursion into it was to verify just what 'supergene' meant. It is "an adjective used to describe ores or minerals formed by processes at the Earth's surface …".

At the end of each chapter there are *Questions and exercises*, which are both interesting and demanding, and require a good deal of thought, time and research. For example, one question that took my fancy, gave a list of about 20 minor minerals not specifically covered in the book, such as antimony, indium, strontium, opal, selenium. You were asked to select one, do a literature search and use the Internet to summarise the geochemistry, uses, history and current importance of the commodity in the world economy.

A novel feature of the book is the use of 'boxes' within the chapters. While not essential reading, these boxes contain more detailed information, bringing an added dimension to the chapters. Boxes cover new research, research techniques and discussions on debates current in ore deposit geology. Some boxes are several pages long, with accompanying illustrations. I liked the optional nature of these boxes — you can take them or leave them.

A list of further reading accompanies each chapter.

Regrettably, the figures didn't appear to have a consistent style. Some figures are clear, with clear descriptions; some are too detailed; some have poor descriptions; and some are simply too small. The figures were usually close to the relevant text, but could be several pages away. Near the beginning of the book they are in the wrong sequence.

In some places the author, in trying to include every possibility, does so at the expense of clarity. He also uses an unusual word order at times that make you pause in reading and ask 'what does the author mean?'

The book professes to be suitable for use late in an undergraduate course or for use in a graduate programme. I felt that it fell between two stools. It was too detailed for a general undergraduate course, only suitable for students who wished to pursue a career in economic geology. As part of a graduate programme I thought the format, with the questions, was a bit inappropriate.

This is literally a heavy book at 1.3kg (almost 3lbs), so not one to take on a flight for light reading! It is thorough in its coverage of worldwide ore deposits and fairly thorough in its coverage of how such deposits form. However, it is not altogether an easy read and requires concentration to get the most out of it.

— Susan Pyne (Branch Organiser, OUGS Ireland)

A typology for hazards and risks as vectors of change and the implications for integrated coastal management

Prof. Mike Elliott

(Director, Institute of Estuarine & Coastal Studies, Prof. of Estuarine & Coastal Sciences, University of Hull, Hull, HU6 7RX) (Mike.Elliott@hull.ac.uk)

Abstract

This article presents a typology for natural and anthropogenic coastal hazards, the evidence for their causes and [their] consequences, especially for society, and their role as vectors of change. A hazard is the potential that there will be damage to the natural or human system, and so is the product of an event that could occur and the probability [that it will occur]. The degree of risk then relates to the amount of assets, natural or societal, that may be affected. The typology indicates 14 hazard types for natural and societal systems, and gives examples of the hazard types and risks. In presenting long- and short-term, and large- and small-scale perspectives, this article shows that the hazards leading to disasters will include flooding, erosion and tsunamis, among other [events], as well as types of erosion. Global examples include the effects of wetland loss and the exacerbation of problems by building on vulnerable coasts. I emphasise the importance of considering the hazards and risks on such coasts, and consider the tools for assessing and managing the impacts of risks and hazards. These [factors help policy-makers] to determine the consequences for natural and human systems. I separate locally derived problems from large-scale effects, such as climate change, sea-level rise and isostatic rebound as unmanaged exogenic pressures whereby [planners can] respond to the consequences rather than to the causes. I conclude by emphasising that integrated and sustainable management of hazards and risks requires ten [defined] tenets to be fulfilled.

[OUGS Canterbury Symposium: Marine Geotales; original transcription by Sally Munnings from the seminar recording; written up by Prof. Elliott, and edited by POUGS Editor David M. Jones]

Introduction

This review discusses the way we use scientific information in relation to hazards and risk, especially in the marine environment, although these messages probably apply for all environments. When we are trying to manage environments there is only one big idea from which everything else follows: How do we protect the natural system and at the same time deliver what society wants?

When we are managing these systems we are coping with all the problems both those we have created in the past and also those that the natural system has created; we can separate these into 'exogenic unmanaged pressures', and 'endogenic managed pressures' (Elliott 2011). An exogenic unmanaged pressure is something that is happening outside the system that you are trying to manage; you are not managing the causes of it, but you have to deal with and manage the consequences. For example, climate change is an exogenic unmanaged pressure when you are managing a piece of sea or coast — you are not managing the causes of it, which is a global problem, but you have to manage the consequences. In contrast, the endogenic managed pressures are things that happen within your system, over which you have some control, and for which you can manage both causes and consequences. I will try and illustrate these.

The main questions are where do our environmental problems come from and how do we manage them. This requires you to think outside your own discipline and, in particular, to link across natural and social sciences.

Hazards and risk analysis

Firstly, hazards and risks. A hazard is where something is going to happen and the risk is: 'Is it going to impact something that we are interested in or we value?' So there are going to be lots of hazards, but they do not always turn into risks (Elliott *et al.* 2014). Hence the importance of risk analysis, and many of us dealing with environmental problems are dealing with risk analysis; we are analysing and assessing risks, we are trying to find out more about them and we are going to do something about them, or hope that society can do something about them. Within this we have a whole set of philosophies. Some of you will be familiar with the DPSIR approach: the set of *Drivers* — the big demands of society such needing food, travel and space. These can create *Pressures* — we are going to go out and trawl the seabed for example; we are going out to build things. Those pressures are mechanisms that then create a *State change* on the natural system — they mess up the ecology for us. If we are not careful, that gives us an *Impact* on society. So, if we go out trawling and we take the fish, it impacts on the natural populations and sooner or later there are no fish for us, so there is an impact on us. So we do something about it — we have a *Response*, which may require economical, legal or administrative instruments (e.g. the Common Fisheries Policy). More recently, DPSIR has been changed to DAPSI(W)R with the addition of *Activities*, which cause pressures and state changes, which in turn impact on societal *Welfare* (Elliott 2014; Fig. 1).

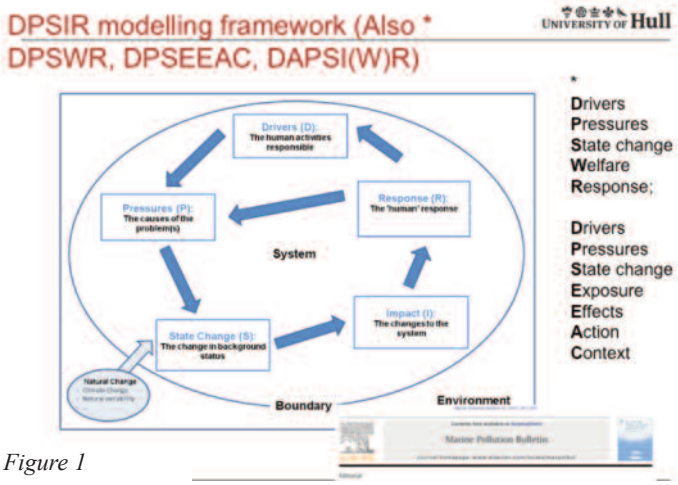


Figure 1

© OUGS ISSN 2058-5209

* *Unfortunately, some of the image files for Prof. E;lliott's article are of low resolution. We have had to push them beyond the usual minimum limits for resolution — Ed.*

There are many activities and pressures in any one area (Atkins *et al.* 2011). For example, wild fishing — and that has all its pressures, state changes and impacts, and we have instruments such as the Common Fisheries Policy as a response. Next might be aquaculture, then navigation, creation of infrastructure and so on — each of these creates changes in the natural state and impacts on human welfare and so needs a response. All of this occurs within an area that we try to manage — hence the term endogenic managed pressures.

Happening outside the management area are the exogenic unmanaged pressures, in which we do not have control over the causes, but we need to respond to the consequences. A good example is climate change. The problem is that when we start trying to manage the system we have to try to manage an area knowing what is going on outside that area. For example, climate change is a global phenomenon, which requires global action on the causes, but local responses (for example on sea-level rise). Similarly, changes in a catchment will be exogenic if the management area is the estuary or coast, but endogenic if the management area is the whole freshwater-estuarine-marine system. Hence we need to study not only an estuary, but also the upstream activities and pressures, and those out at sea — so the distinction between endogenic and exogenic aspects become quite important.

Because of this, it is necessary to consider what things over which we have and do not have control, and hence the need for a hazard and risk typology (Elliott *et al.* 2014) (Table 1).

Table 1 Typology of Hazards in Coastal and Coastal Wetland Area (taken from Elliott *et al.* 2014)

hazard	***type***	***examples***
(A) surface hydrological hazards	natural, but exacerbated by human activities	high tide flooding, spring tide and equinoctial flooding; flash flooding, ENSO/NAO patterns
(B) surface physiographic removal by natural processes — chronic/long-term	natural, but exacerbated by human activities	erosion of soft cliffs by slumping
(C) surface physiographic removal by human actions — chronic/long-term	anthropogenic	land claim, removal of wetlands for urban and agricultural area
(D) surface physiographic removal — acute/short-term	natural	cliff failure, undercutting of hard cliffs
(E) climatological hazards — acute/short-term	natural, but exacerbated by human activities	storm surges, cyclones, tropical storms, hurricanes, offshore surges, fluvial and pluvial flooding
(F) climatological hazards — chronic/long term	natural, but exacerbated by human activities	ocean acidification, sea level rise, storminess, ingress of seawater/saline intrusion
(G) tectonic hazards — acute/short-term	natural	tsunamis, seismic slippages
(H) tectonic hazards — chronic/long-term	natural	isostatic rebound
(I) anthropogenic microbial biohazards	anthropogenic	sewage pathogens
(J) anthropogenic macrobial biohazards	anthropogenic	alien, introduced and invasive species, GMOs, bloom-forming species
(K) anthropogenic introduced technological hazards	anthropogenic	infrastructure, coastal defences
(L) anthropogenic extractive technological hazards	anthropogenic	removal of space, removal of biological populations (fish, shellfish, etc); seabed extraction and oil/gas/coal extraction leading to subsidence
(M) anthropogenic acute chemical hazards	anthropogenic	pollution from one-off spillages, oil spills
(N) anthropogenic chronic chemical hazards	anthropogenic	diffuse pollution, litter/garbage, nutrients from land run-off, constant land-based discharges, aerial inputs

The first set — the surface hydrological hazards such as flooding, are of current importance if you live on the Somerset Levels or the Norfolk Broads. These problems are natural problems, but they are exacerbated by our response or lack of it. For example, much of the city of Hull is low lying and would get flooded if there were no sea defences around the Humber. Hence the need for the tidal surge barrier. Flood Risk Management Strategies, etc. are required, and measures are costly, but required to protect assets and public safety. Reductions in public spending have recently affected these measures.

The next type is the removal of the area that may be natural, but made worse by our actions. The Holderness (East Yorkshire) coast is typical of this — it is an eroding coast, comprising glacial tills and migrating landward by 1–2m a year. Residents try to do something about it individually by putting in futile sea defences and the sea just comes behind them and exacerbates the problem. Hence we get newspaper headlines about it. Preventing erosion by using soft-engineering such as groynes may trap sediment and slow the erosion in one area, but starve a beach of sediment downstream and make the erosion worse. The erosion is a natural phenomenon, it is going to happen and has been happening since the last ice age, but we can make it worse. The recent approach is adaptation by having a 'roll-back' process where residents are discouraged from occupying the land — even with incentives to move from the coast.

The next type is our removal of the area — what we used to call reclamation, but now called land claim. The 1794 map of the Humber Estuary shows large areas of wetlands, and an island, Sunk Island, whereas the current area shows those areas to be removed. Removing the wetlands for agriculture has created problems that we now have to address, especially as we have squeezed the estuary. If you squeeze the water going into the estuary so it cannot move sideward it can only increase in height, which gives us problems — thus needing increased defences. Land claim also creates problems for the natural system because we are losing a lot of the natural functioning in the system, such as the feeding areas for wading birds and juvenile fish.

The next type is the acute removal of material — such as cliff failures, undercutting and so on. For example, at Runswick Bay on the North Yorkshire coast, an area where the cliff has failed and is collapsing, putting expensive properties at risk and requiring urgent action. This involved re-engineering the coast, sculpturing the coast and creating a more stable coastline. A second example is Holbeck Hall Hotel, Scarborough, which 21 years ago started sliding into the sea (see http://www.bgs.ac.uk/landslides/holbeckHall.html). Overnight the garden and then the house collapsed, thus removing valuable assets. Again urgent action was required to stabilise the coast and to prevent further damage to adjoining houses.

The next type are the climatological hazards, such as storm surges, which are a particular problem on the east coast of England and all low-lying coasts — thus affecting large numbers of residents and industries. The cause cannot be controlled, but the consequences need addressing. Storm surges occur through the combination of winds in a certain direction, low pressure to cause the water to rise, high (spring) tides and possibly elevated rainfall. The storm surge in 1953 killed about 2,000 people around the North Sea, mostly in the Netherlands, and this led to major engineering works (e.g. the Dutch Deltaplan) where they have put in barriers and modified coasts to cope with these (Gerritsen 2005). A similar storm surge in December 2013 was as large, but did not create the same severe consequences because of large measures taken in recent decades, such as the Thames Barrier.

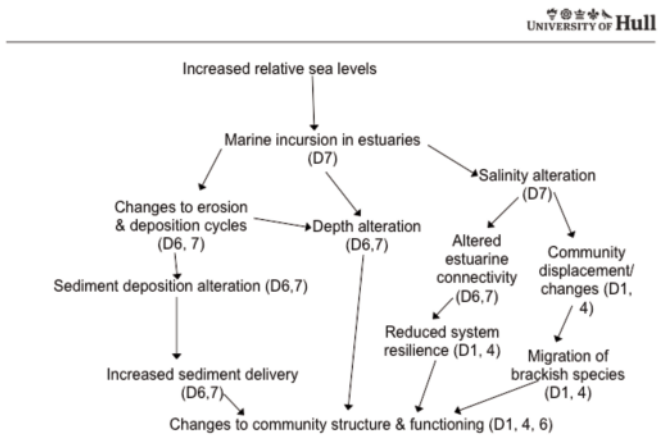
Some of the long-term climatological hazards — the less dramatic ones, e.g. ocean acidification, sea-level rise, storminess and so on — may have natural causes (such as land subsidence, discharges from undersea vents), but we are also exacerbating their effects. Climate change is going to affect the way we manage the coast, but there are repercussions of increased relative sea-level rise, a decrease in pH and the increase in CO_2. Such changes have occurred before, but not at the same speed as they do today.

Next there are tectonic hazards — the acute and the short-term ones, the tsunamis and seismic slippages. Just as an illustration, the way we respond and the way we use or manage systems actually makes this system worse. In comparing pictures of Indonesia before and after the tsunami of Christmas 2004, the areas that were most devastated were the ones where we have removed mangroves, which previously absorbed the energy from these events. We removed mangroves to create shrimp ponds and fish farms, or land for living or agriculture, but this made the effects of the tsunami much worse by removing natural protection and resilience. In north-west Europe, it is exactly the same if we remove protective salt marshes and reed beds. Unfortunately, tsunamis are natural events and cannot be stopped, but we have to respond to the consequences, we have to be prepared for it and we should reduce the effects by allowing the natural buffering capacity to remain.

The chronic long-term tectonic hazards — such as isostatic rebound — are especially prevalent in south-eastern Britain, although there is much uncertainty about the exact Relative Sea Level Rise (RSLR, in mm) owing to isostatic rebound (Fig. 2). The Environment Agency and the other flood-risk people have to take account of this as we have not just got rising seas owing to global warming, we have also got subsiding land — so we talk about relative sea-level rise. Those living in Scotland or Scandinavia are more fortunate, as the land is rising!

The next group of hazards are the things we really do cause, where we are the main or sole cause of the problem, such as microbial hazards — which have always been around since we started putting our waste into the nearest water course. Until the early 1990s, a common way of discharging domestic waste at the coast

Figure 2 Diagramatic representation of the effects of isostatic rebound.


University of Hull
Increased relative sea levels
Marine incursion in estuaries (D7)
Salinity alteration (D7)
Changes to erosion & deposition cycles (D6, 7)
Depth alteration (D6,7)
Altered estuarine connectivity (D6,7)
Community displacement/ changes (D1, 4)
Sediment deposition alteration (D6,7)
Reduced system resilience (D1, 4)
Migration of brackish species (D1, 4)
Increased sediment delivery (D6,7)
Changes to community structure & functioning (D1, 4, 6)

Estuarine hydrodynamic changes due to increased relative sea levels leading to ecosystem effects (MSFD Descriptor denoted in brackets)

was through short or long sea outfalls as a way of treating our sewage. Faecal bacteria are killed by being put into the salty waters, into the light, into the cold, although it is not the same for viruses. Therefore, to minimise the effects, we have to manage the system by monitoring the coast and the bathing waters, and by reducing the waste going into the sea — usually by increasing treatment.

Discharging our waste at the coast may not necessarily be a problem until it conflicts with what we want to do, such as bathing or harvesting mussels to eat. We then either have to close beaches for swimming or clean the mussels before we can eat them — so we are responding to the problem, but we should respond to the causes by putting in new sewage works that treat and disinfect the waste. The EU Urban Waste-water Treatment Directive and the Bathing Waters Directive aim to control these problems.

There are other hazards relating to larger organisms (microbial), not just the microbes. We have long put pollutants into the waters — a pollutant is something we put into the system that causes biological harm, such as damage to health. If it does not cause harm, we call it a contaminant. While large organisms have long been put into or have escaped into the waters, only recently have we have started calling these larger organisms biological pollutants, for example non-indigenous or alien species (Olenin *et al.* 2011), because they cause harm to the system. For example, the Chinese mitten crab, which has been in Europe about a century, lives in fresh waters and moves down the estuaries, where it burrows into sea defences, weakens the sea defences and gives us a problem — hence it is defined as a pollutant and is causing a problem for us. However, there is a debate about whether these organism have become naturalised, and so although there may be a problem, it could be regarded as a natural phenomenon.

Technological hazards are the large structures that we create and put in place. The UK is planning to have about 6,000 turbines put into the water by later this decade, and so we need to know what aspects of this technology are going to give us a problem to which we need to respond. By taking the view that each structure has a behaviour (for example, of the monopile put into the seabed, the cabling and the rotating blades), we then need to know the effects of this on the natural system and its components (e.g. Wilson *et al.* 2010). We are required to consider the effects on the iconic nature conservation species, for example the Honeycomb worm *Sabellaria*, which occurs everywhere, including around wind farms, as well as charismatic megafauna such as birds and marine mammals. However, a huge amount of effort goes into assessing the effects of this infrastructure and this effort shows that the problems are relatively minor. Studies show that birds migrate around and through wind farm areas, thus showing a natural adaptation.

Next in the typology are the extractive hazards, where we are removing materials from the seas — it is important to see that the problems in the seas only come from three sources:

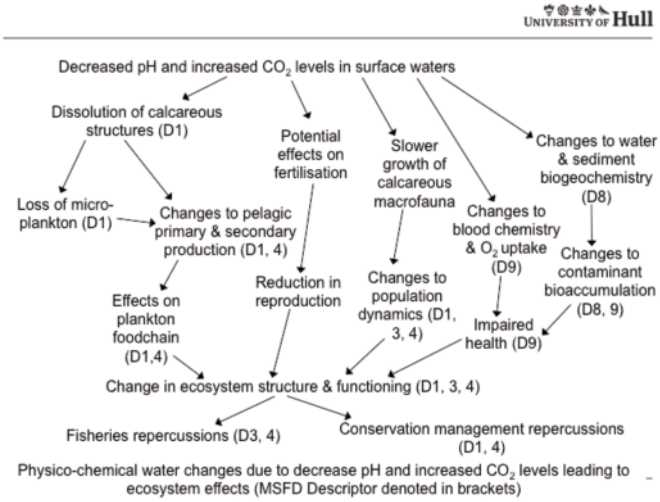
- materials and structures that we put in — such as infrastructure, land-claim, contamination, the resulting pollution;
- materials we that take out — such as space, fish, water, salt and sediment; and
- other external factors — such as global warming and things outside our control.

The removal of space and of marine populations (such as fish) is a legitimate use of the sea, i.e. they are legally sanctioned. We need dredgers, as we have ports and have to dredge those ports to remove the sediment — as it is in the wrong place at the wrong time. In particular, we build ports in sediment-rich estuaries, thus exacerbating the problem. Sometimes it is not just sediment, but garbage that gets put into large boats and sent to be dumped back into the sea. We are managing these areas, but we are also manipulating the system by changing the nature of the seabed such that we might be holding the system in an artificial state (e.g. artificially deepened for navigation), but that is because we want to use the system. For building materials, we extract sand and gravel from the seabed. Hence we have many benefits from the sea and so we have to manage the system for the benefit of those uses and also for the protection of wildlife.

Chemical inputs are another hazard from us, in contrast to the input of natural chemicals — for example oil spills from shipping accidents or illegal washing of tanks. These pose a hazard and become a risk to things we value — fish we want to take or wildlife we value. Society has long put its waste into the sea, causing pollution, and so we have a very good and extensive literature on what happens when we put those pollutants into the system (McLusky and Elliott 2004). We consider such effects on all levels of biological organisation — from the cell, to the tissue and to whole organisms, and then to populations, communities and ecosystems. We make the assumption that continued and increasing levels of pollutants will pass along this chain and cause harm to the higher levels, although each part of that chain has the ability to regulate the pollutant; and problems only occur once that capacity has been exceeded. Hence we have to try to manage the system so that this does not occur. Hence consider the terms we use for assessing that change and that damage to the system — for example, we talk of a diagnosis of ecosystem pathology. These are the same terms that doctors use in order to determine medical problems (Fig. 3).

In considering the fate and effects of pollutants (what may be termed xenobiotics — foreign materials), we assume that such changes go through all the parts of the system; that they affect the genetics, the physiology, the biochemistry, the community, the ecology, and eventually might affect humans by reducing the yields of fish and so on (Elliott and Hemingway 2002). However, within this model is what we call environmental homeostasis, the ability of the system to absorb stress such that the pollutants do not necessarily cause severe problems (Elliott and Quintino 2007).

Figure 3 Diagramatic representation of chemical input hazards.


University of Hull
Decreased pH and increased CO_2 levels in surface waters
Dissolution of calcareous structures (D1)
Potential effects on fertilisation
Slower growth of calcareous macrofauna
Changes to water & sediment biogeochemistry (D8)
Loss of micro-plankton (D1)
Changes to pelagic primary & secondary production (D1, 4)
Changes to blood chemistry & O_2 uptake (D9)
Changes to contaminant bioaccumulation (D8, 9)
Effects on plankton foodchain (D1,4)
Reduction in reproduction
Changes to population dynamics (D1, 3, 4)
Impaired health (D9)
Change in ecosystem structure & functioning (D1, 3, 4)
Fisheries repercussions (D3, 4)
Conservation management repercussions (D1, 4)
Physico-chemical water changes due to decrease pH and increased CO_2 levels leading to ecosystem effects (MSFD Descriptor denoted in brackets)

There are some examples of this sequence. For example, mercury poisoning from a chlor-alkali plant in Minimata Bay, Japan in the last century, in which marine fish and shellfish accumulated the pollutant, which then led to deaths and birth anomalies in the local human population.

The last hazard to consider is diffuse pollution, by definition the things that are very difficult to control. Point-source pollution — such as a pipeline discharge from a chemical or sewage works, or an oil spill — is relatively easy to control. In contrast, diffuse pollution — such as run-off from agriculture (pesticides and nitrates and so on), or oils from hard-standing areas such as roads and car parks — is difficult to control; and even though it may be in low concentrations, the amounts can build up in the receiving waters over time. In the case of excess fertilisers, these lead to changes in the system, such as algal mats, as the nutrients get retained and produce a whole suite of undesirable symptoms termed eutrophication (de Jonge and Elliott 2001). Nutrients going into the system result in symptoms such as red tides, noxious blooms, changes to the plankton system (such as plankton that can be poisonous and give us shellfish poisoning), killing off the fish due to shellfish poisoning, or changes to the organic matter, changing the nature of the sea bed (leading to far fewer and only pollution-tolerant species (Gray and Elliott 2009). The excess organic matter has an oxygen demand and so can produce a barrier to fish migrating. These consequences are well known and we can do something about them — for example having treatment works; low level run-off, however, is much more difficult to control. There are management systems and international agreements that enable us to control all this — for example, putting buffer zones around fields, applying nutrients at drier times of the year or creating nitrate-vulnerable zones in which fertilisers are controlled.

Environmental management framework

The overall framework for these 14 types of hazards (Elliott *et al*. 2014) shows a sequence from the natural to man-made problems, from the involuntary (things we are not controlling) up to the voluntary ones, and the intense, the diffuse and the point-source problems. Therefore there is a good knowledge and understanding of these problems such that we can tell the environmental managers where the problems are coming from and what we can do about them, hence leading to an 'environmental management framework'.

Recently, in Cormier *et al.* (2013), we looked at this evidence in risk-based management and considered a particular technique, 'Bow-tie analysis', previously used in industry and now used in environmental sciences. This focuses on a major concern or hazard that is causing a risk; this has a set of causes and if it occurs, a set of consequences. Therefore we need to put in a set of preventative measures to try to stop the threats creating this top event, and if the prevention does not work then we put in mitigation and sometimes compensation to stop these consequences.

For example, as part of a large European project (VECTORS, http://www.marine-vectors.eu/) we have been assessing not just the effects of offshore wind power, but rather the effects of climatic change such as storm surges on the creation of offshore wind power, hence causing concern if the wind power fails. Industry has long been using Bow-tie software for risk assessment and risk management, and hence this is now being taken into the environmental sciences to indicate what can be done about the problems, what are the barriers we can put into place, what are the preventative measures and mitigation measures we can put into place. However, this does get complicated, because the natural environment is complex.

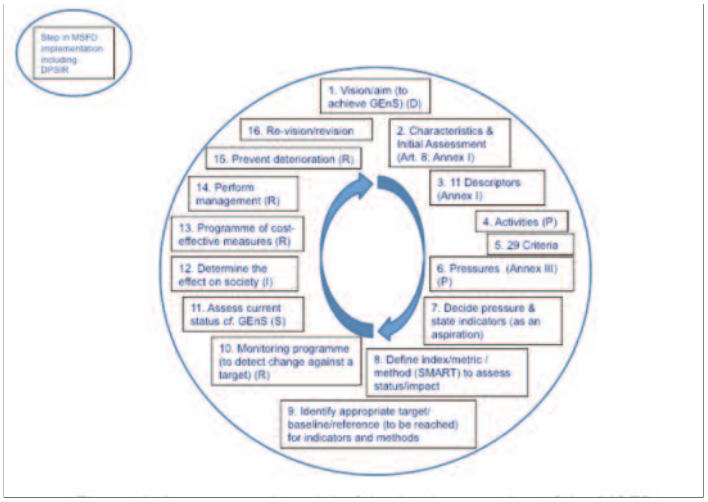
This is really to make the point that we are interested in the natural system, the way that physics creates the ecology, and the way the natural system is created and functions, and then in the effects of societal demands on all of these aspects. But, more importantly, if we go and talk to politicians, and the environmental managers, they are interested in the money — the economy. So now we are working in these terms — we focus on what are termed ecosystem services leading to ecosystem goods, leading to societal benefits, and that is what we are trying to protect (Atkins *et al.* 2011). Governments in many countries are now saying that the economy is much more important than the environment, which brings us back to managing the environment for the benefit of both the natural and human systems.

As indicated here, we do have an elaborate governance system (of policies, politics, administration and legislation) to control the adverse consequences of our actions. The governance complexity of the system is shown in what we call 'The Ultimate Horrendogram' (Boyes and Elliott 2014), which indicates the control and management. If you go to industry and say it would be a good idea if you just do this or there is a guideline here — they respond that they will go and discuss it with the shareholders. If you say there is a piece of law, which if not followed, then you are going to court or your country will go to the European Court, then it focuses their minds.

Boyes and Elliott (2014) looked at all the legislation that is controlling the marine environment, including the UN Law of the Sea, the Kyoto Protocol and the UN Convention of Biological Diversity. These are the global aspects. On top of that are the European Directives that a Member State has to follow, together with the actions that these require countries to take. Following this there is the national legislation, for example the English legislation and what the English legislation requires of industry and statutory bodies. These together give a cascading system, what is known as a vertical integration of governance. Hence we have to meet all the global agreements, EU Directives and English/UK legislation if we want to meet the government vision of healthy, productive, safe, clean and biologically diverse seas; if we do not achieve this, then we could take all benefits from the seas.

An example of the legislation is the EU Marine Strategy Framework Directive, which relies on us defining the activities and pressures in the sea and their effects on a set of characteristics called 'descriptors'; our assessments then aim to determine whether we have achieved Good Environmental Status (Borja *et al.* 2013; Fig. 4, *overleaf*).

Hence, this is where the distinction between endogenic and exogenic pressures is valuable, because we have to know what are the problems within our control and what are outside our control. We have systems of restoring and re-creating — making good the problems we have caused over the years — where we attempt to re-create habitats, restore habitats and recover things; and we have got the management techniques to do that (Elliott *et al.* 2007). These things, again, cross-refer to the diagnosis of pathology and the similarity between what we are doing in environmental management and what the medics are doing — we are doing exactly the same thing in the environment. We assess (diagnose), predict (give a prognosis), give treatment (remediate) and hope to prevent problems (management). We have a whole


1. Vision/aim (to achieve GEnS) (D)
2. Characteristics & Initial Assessment (Art. 8; Annex I)
3. 11 Descriptors (Annex I)
4. Activities (P)
5. 29 Criteria
6. Pressures (Annex III) (P)
7. Decide pressure & state indicators (as an aspiration)
8. Define index/metric / method (SMART) to assess status/impact
9. Identify appropriate target/ baseline/reference (to be reached) for indicators and methods
10. Monitoring programme (to detect change against a target) (R)
11. Assess current status cf. GEnS (S)
12. Determine the effect on society (I)
13. Programme of cost-effective measures (R)
14. Perform management (R)
15. Prevent deterioration (R)
16. Re-vision/revision

Figures 4 The Marine Strategy Framework Directive and a model for its implementation.

set of systems for assessing if these hazards have done harm or how to stop these hazards from doing harm, such as Environmental Impact Assessments, Habitat Regulation Assessments and other things as required by European Directives and national laws.

This then brings us to consider what is required for successful and sustainable environmental management. This may be summarised as the '10-tenets' (Table 2; Elliott 2013). In order to get sustainable management of all these hazards and risks, first of all we want the ecology to be sustainable, as otherwise nature conservation and biodiversity are affected. We need the technology to be able to do something — can we build the right sort of treatment works; can we put in the remediation; and so on. But we live in the real world, so we also have to decide if we have got the money to do it — the economy. Then we need to consider what does society want and what does society desire or tolerate. For example, society does not desire that our waste goes out into the sea, but it tolerates it because it knows it is a cheap disposal route. Next we need the legal framework, as described above, that covers the international, European and national realms, and is certainly comprehensive. Then we need the administrators (the ministries, agencies, departments, etc.) to enact that governance (Boyes and Elliott 2015); and also the political dimension — is there political expedience — without making a political point, such as a Prime Minister recommending "hugging a husky" (as well as "hugging a hoodie") one year, and "kicking out the 'green crap'" the next!

Table 2 The 10-tenets — to be successful, sustainable management measures or responses to changes resulting from human activities should be (from Elliott 2013)

1. ecologically sustainable
2. technologically feasible
3. economically viable
4. socially desirable/tolerable
5. legally permissible
6. administratively achievable
7. politically expedient
8. ethically defensible (morally correct)
9. culturally inclusive
10. effectively communicable

We then need to consider whether environmental management is ethically defensible — for example, we want to improve the environment so we are going to commit to spend a lot of money to do so; we have not got the money, so we are going to load it onto our kids and our grandchildren — estimating the eventual costs is called 'discounting' in economic terms. Is that ethically defensible? Our generation made the mess, but are future generations going to pay for it? Next is whether our actions are culturally inclusive — in some countries any proposed developments that affects the indigenous population will be stopped without question. Finally, all of these other nine aspects need to be effectively communicated to get the agreement of all stakeholders (Fig. 5, *opposite*).

Concluding comments

As shown in the diagrams in Elliott (2014), there are many activities in the environment — things that we take out of the system, things that we put into the system, things that are wider pressures such as climate change. These all potentially cause problems either for the natural system or for society. To assess these problems we need to do risk assessment and risk management, as well as follow frameworks such as DAPSI(W)R and conflict-resolution techniques. There is extensive governance and we have to ensure that this is vertically integrated — from the global down to the local. We have many stakeholders who need to be involved in order to get the system sustainable: the regulators, the extractors, those affected by this, the people who are influencing it; and there needs to be horizontal integration across these stakeholders.

We then need to show who benefits from all this — we want all these societal benefits and the ecosystem services out of the system, and the reason we are doing all of this is because of something that all our countries have signed up to — the Ecosystem Approach. This is what is regarded here as 'the big idea' — this is how we protect the natural system and, at the same time, deliver what society wants. If we only get one of these things — if we protect the natural system but do not deliver what society wants — then there are no jobs, but the 'tree-huggers' are happy. If we only deliver what society wants and we ruin the environment, the conservation lobby is not very happy, but the 'industrial warriors' are happy.

Hence, the Ecosystem Approach is paramount.

To finish, we can discuss impediments to achieving the sustainable

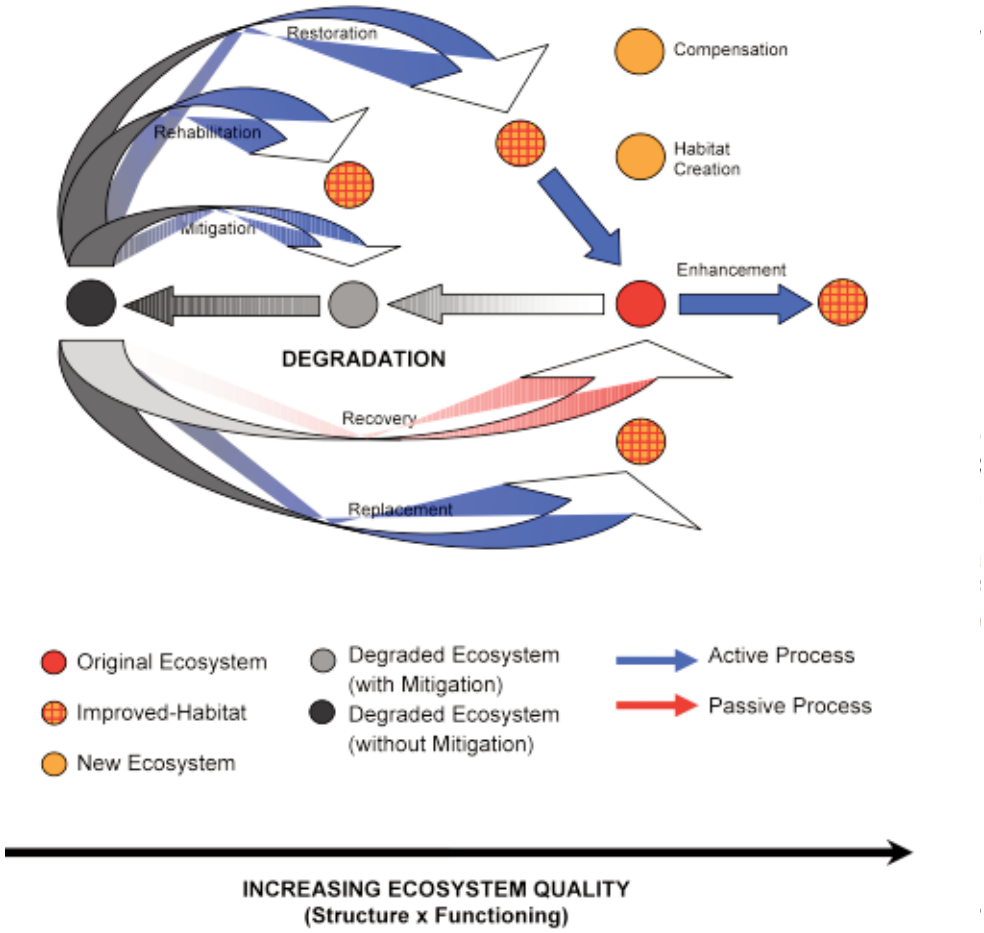


Figure 5 Estuarine coastal and marine restoration: confusing management and sceince — a revision of concepts (Michael Elliott, Daryl Burdon, Krystal L. Hemingway, and Sabine E. Apitz).

management — what industry terms 'bottlenecks', 'show stoppers' and 'train wrecks' as an indication of the size of the problem, the possible measures and the impediments to solutions. A 'bottleneck' is something that will be solved on its own fairly quickly, a 'show stopper' takes a bit more effort to solve the problem, but 'train wrecks' are the impediments that cause greatest concern — such as political intransigence, or a lack of funding or of the expertise to solve the problems. This shows the importance of quality assurance and decision making, the risk framework, DAPSI(W)R and the 10-tenets. The feedback loops are also in this process — what are we doing now that is going to affect things in the future and so on, hence building on the systems we have already got.

This article shows that we now have a sufficiently good understanding of what the hazards are and the risks they cause, and what can we do about some of them (whether we can tackle the cause and the consequences of some, whereas some others we can only tackle the consequences, because the cause needs global action or, as in the case of tsunamis, we cannot do anything about them — all we can do is be prepared for them).

Finally, I hope I have shown that we cannot do this by sitting in silos, we cannot be only natural scientists, biologists, geologists, chemists or physical scientists. In order to get people to take notice of the messages — to bring it into the social system — we have to merge ideas from politics, economics and technology (Fig. 6, *overleaf*).

References and further reading

Atkins, J. P., Burdon, D., Elliott, M., and Gregory, A.J. 2011 'Management of the marine environment: integrating ecosystem services and societal benefits with the DPSIR framework in a Systems Approach'. *Marine Pollution Bull* **62**, 215–26

Borja, A., Elliott, M., Andersen, J. H., Cardoso, A. C., Carstensen, J., Ferreira, J. G., Heiskanen, A-S., Marques, J. C., Neto., J., Teixeira., H., Uusitalo., L., Uyarra., M. C., and Zampoukas, N. 2013 'Good environmental status of marine ecosystems: what is it and how do we know when we have attained it?' *Marine Pollution Bull* **76**, 16–27

Boyes, S. J., and Elliott, M. 2014 'Marine legislation — the ultimate 'horrendogram': international law, European directives and national implementation'. *Marine Pollution Bull* **86**, 39–47

Boyes, S. J., and Elliott, M. 2015 'The excessive complexity of national marine governance systems — has this decreased in England since the introduction of the Marine and Coastal Access Act 2009?' *Marine Policy* **51**, 57–65

Cormier, R., Kannen, A., Elliott, M., Hall, P., and Davies, I. M. (eds) 2013 *Marine and Coastal Ecosystem-based Risk Management Handbook*.

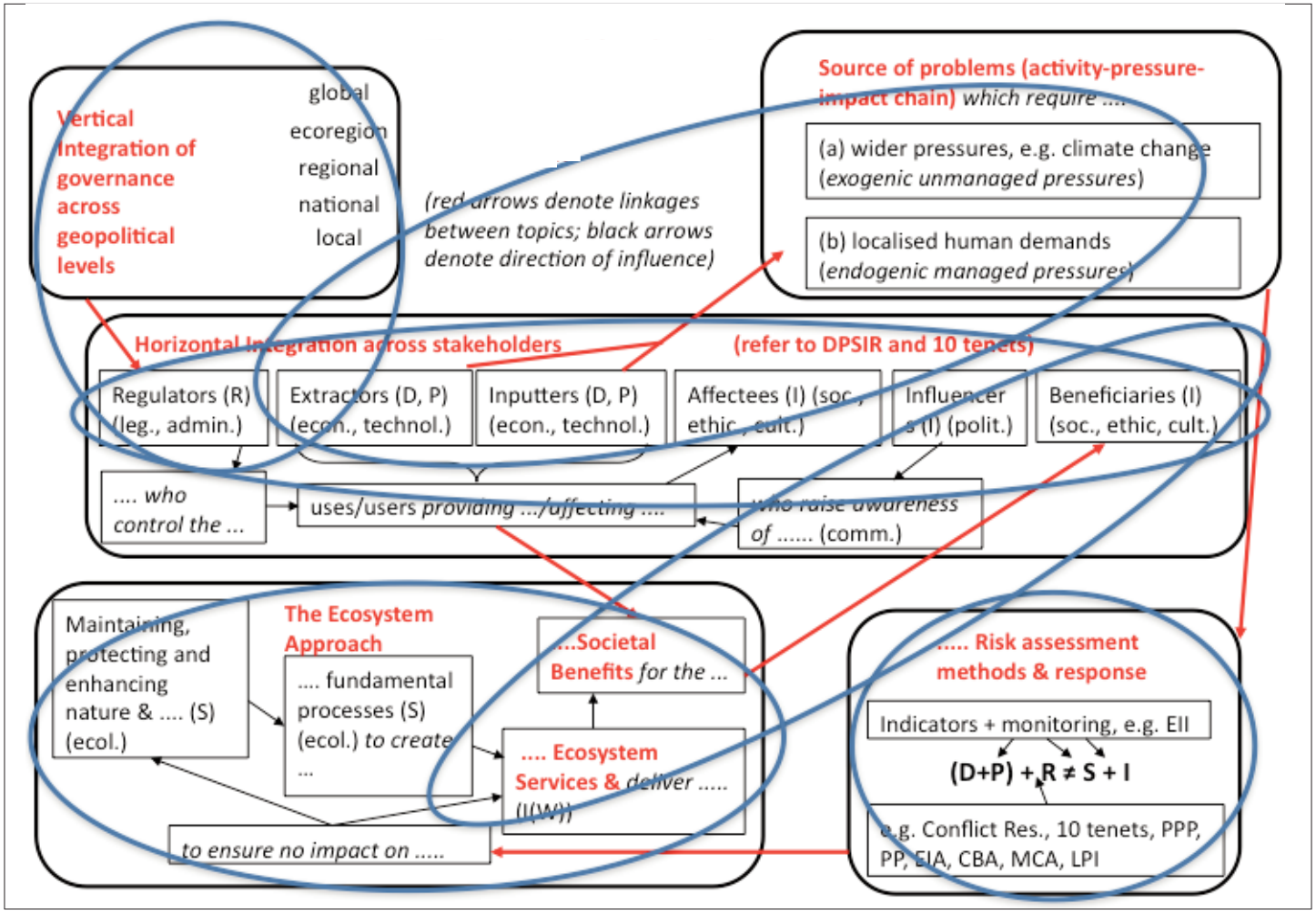

Vertical Integration of governance across geopolitical levels
global
ecoregion
regional
national
local
(red arrows denote linkages between topics; black arrows denote direction of influence)
Source of problems (activity-pressure-impact chain) which require ....
(a) wider pressures, e.g. climate change (exogenic unmanaged pressures)
(b) localised human demands (endogenic managed pressures)
Horizontal Integration across stakeholders
(refer to DPSIR and 10 tenets)
Regulators (R) (leg., admin.)
Extractors (D, P) (econ., technol.)
Inputters (D, P) (econ., technol.)
Affectees (I) (soc., ethic., cult.)
Influencers (I) (polit.)
Beneficiaries (I) (soc., ethic, cult.)
.... who control the ...
uses/users providing .../affecting ....
who raise awareness of ..... (comm.)
Maintaining, protecting and enhancing nature & .... (S) (ecol.)
The Ecosystem Approach
.... fundamental processes (S) (ecol.) to create ...
...Societal Benefits for the ...
.... Ecosystem Services & deliver ..... (I(W))
to ensure no impact on .....
..... Risk assessment methods & response
Indicators + monitoring, e.g. EII
(D+P) + R ≠ S + I
e.g. Conflict Res., 10 tenets, PPP, PP, EIA, CBA, MCA, LPI

Figure 6 Considerations in holistic and adaptive environmental management.

ICES Cooperative Research Report No. 317, March 2013, International Council for the Exploration of the Sea, Copenhagen

De Jonge, V.N., and Elliott, M.(2001 'Eutrophication', *in* Steele, J., Thorpe, S., and Turekian, K. (eds) *Encyclopedia of Ocean Sciences, Volume 2*. London: Academic Press, 852–70

Elliott, M. 2011 'Marine science and management means tackling exogenic unmanaged pressures and endogenic managed pressures – a numbered guide'. *Marine Pollution Bull* **62**, 651–5

Elliott, M. 2013 'The 10-tenets for integrated, successful and sustainable marine management'. *Marine Pollution Bull* **74**, 1–5

Elliott, M. 2014 'Integrated marine science and management: wading through the morass'. *Marine Pollution Bull* **86**, 1–4

Elliott, M., and Hemingway, K. L. (eds) 2002 *Fishes in Estuaries*. Oxford: Blackwell Science

Elliott, M., Burdon, D., Hemingway, K. L., and Apitz, S 2007 'Estuarine, coastal and marine ecosystem restoration: confusing management and science — a revision of concepts'. *Estuarine, Coastal and Shelf Science* **74**, 349–66

Elliott, M., and Quintino V. 2007 'The estuarine quality paradox, environmental homeostasis and the difficulty of detecting anthropogenic stress in naturally stressed areas'. *Marine Pollution Bull* **54**, 640–5

Elliott, M., Cutts, N. D., and Trono, A. 2014 'A typology of marine and estuarine hazards and risks as vectors of change: a review for vulnerable coasts and their management'. *Ocean and Coastal Management* **93**, 88–99

Gerritsen, H. 2005 'What happened in 1953? The Big Flood in the Netherlands in retrospect'. *Philosoph Trans Roy Soc A* **363**, 1271–91

Gray, J. S., and Elliott, M. 2009 *Ecology of Marine Sediments:Sscience to Management*. Oxford: OUP

McLusky, D. S. and Elliott, M. 2004 *The Estuarine Ecosystem: Ecology, Threats and Management* (3rd edn). Oxford: OUP

Olenin, S., Elliott, M., Bysveen, I., Culverhouse, P., Daunys, D., Dubelaar, G. B. J., Gollasch, S., Goulletquer, P., Jelmert, A., Kantor, Y., Mézeth, K B., Minchin, D., Occhipinti-Ambrogi, A., Olenina, I., and Vandekerkhove, J. 2011 'Recommendations on methods for the detection and control of biological pollution in marine coastal waters'. *Marine Pollution Bull* **62**, 2598–2604

Wilson, J. C., Elliott,M., Cutts, N. D., Mander, L, Mendao, V., Perez-Dominguez, R., and Phelps, A. 2010 'Coastal and offshore wind energy generation: is it environmentally benign?' *Energies* **3**, 1383–422

Oil and gas exploration in the Arctic

Prof. Alastair J. Fraser

(EGI Chair in Petroleum Geoscience, Imperial College London)

Abstract

The vast Arctic region is probably the last remaining unexplored source of conventional hydrocarbons on the planet.

In the past three decades of oil exploration in the Arctic, more than 200 billion barrels of oil have been discovered. Ultimate resources are estimated at 114 billion barrels of undiscovered oil and 2,000 trillion cubic feet of natural gas. If these estimates are correct, then these hydrocarbons would account for more than a fifth of the world's undiscovered reserves. This great prize, in a world of diminishing resources, has stimulated both governmental and industrial interest in areas such as the Canadian Beaufort Sea, East and West Greenland, and the Kara Sea.

Balanced against this interest in extracting these resources are the considerable technical challenges of exploring and producing hydrocarbons in areas where sea ice is present for more than half the year, as well as the underlying threat of damage to a pristine Arctic environment.

Harnessing the considerable resources of the 'Final Frontier' is going to be fraught with many technical, political and environmental challenges that will engage many minds, both scientific and political, over the next half century.

[OUGS Canterbury Symposium: Marine Geotales; original transcription by Rosemary Darby from the seminar recording; edited by Prof. Fraser and POUGS Editor David M. Jones]

Introduction

Why should I be talking to you about the Arctic at what is essentially an oceanographic conference? The connection I'm going to make is the frozen Arctic Ocean, or at least the geology that underlies the extensive Arctic ice cap. When I joined the oil industry in 1977, my first international assignment was to Anchorage in Alaska, then up beyond the Arctic Circle to the North Slope. I instantly fell in love with the Arctic, a beautiful, pristine wilderness. [We] were drilling for oil and gas at the time, [and] I had several concerns about this type of activity up there — and now [that] I am in academia, I can perhaps give you a more balanced view [about] what the implications are in terms of what resources are up there, what problems [face] us in terms of the technology in extracting these resources should we chose to pursue them, but probably most of all, [about] the politics involved. As you probably know there is a lot of politics involved in exploiting oil and gas everywhere, but particularly the Arctic.

I [will put] as many facts in front of you as I can. [Also] a little bit of interpretation on the geological side — I'm allowed to do that since I'm a geologist; but I'll try to stay factual [about the] technology, politics and the environment.

The underlying geology

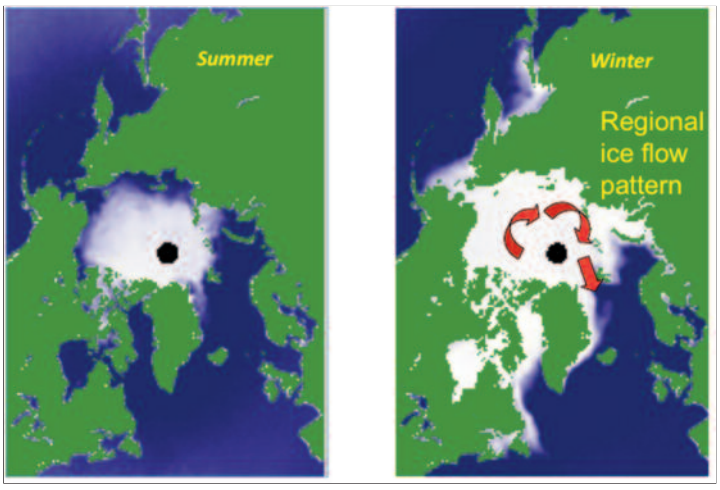
There [are] four main themes [that I would] like to address: first, do we need to go to the Arctic? Is there a plan B we could use? Let's talk a bit about geology; let's just strip off the ice and [see] what the geology [is] like beneath the Arctic Ocean? Is it all ocean; is it oceanic crust; or is there some continental crust there? Why are all these countries fighting over bits of the continent, planting flags? [I'll] talk a bit about the technology because it is the last frontier for conventional hydrocarbons on the planet, should we wish to exploit it; [I'll] talk about who owns the Arctic, the politics involved and who are going to be the major players if this does happen. [I'll also talk about the] Exxon Mobil drilling a well in the Arctic.

According to the United States Geological Survey (USGS), there is potentially a lot of oil and gas in the Arctic. I happen to agree with them. I don't necessarily agree [that] there is a lot more gas than oil — I think it's going to be very oily and that will bring its own problems. A lot of major oil companies are getting interested and spending rather large amounts of money [exploring]. I'm not going to go into extensive detail on all this, but one of the first things [follows] on from the Norwegians and Russians agreeing a median line between Norway and Russia in the Barents Sea. We're going to see activity in the region very soon.

Exxon Mobil have signed an agreement to explore the Russian Arctic with the Russian oil company Rosneft. They have recently conducted exploration drilling in the South Kara Sea. Shell have had major delays to planned operations in the Chukchi Sea off Alaska — they've reportedly spent $6 billion in the Chukchi Sea just off Alaska, [on] the US side and haven't drilled a single well [yet]. A lot of companies have just signed licences with the Danish / Greenland government to drill in East Greenland — one of the worst places on the planet to actually go drilling, from an environmental point of view.

Now here's the Arctic. First of all we've got to think of the Arctic in a different way from the rest of the world (Fig. 1). We have to use polar projections, otherwise Greenland looks enormous, Siberia looks enormous. We have to look down at the planet from the top. In the winter the Arctic is still covered in ice and is still dark 24 hours a day north of the Arctic circle, which is

Figure 1 Summer and winter ice.*



© OUGS ISSN 2058-5209

* *Unfortunately, some of the image files for Prof. Fraser's article are of low resolution. We have had to push them beyond the usual minimum limits for resolution — Ed.*

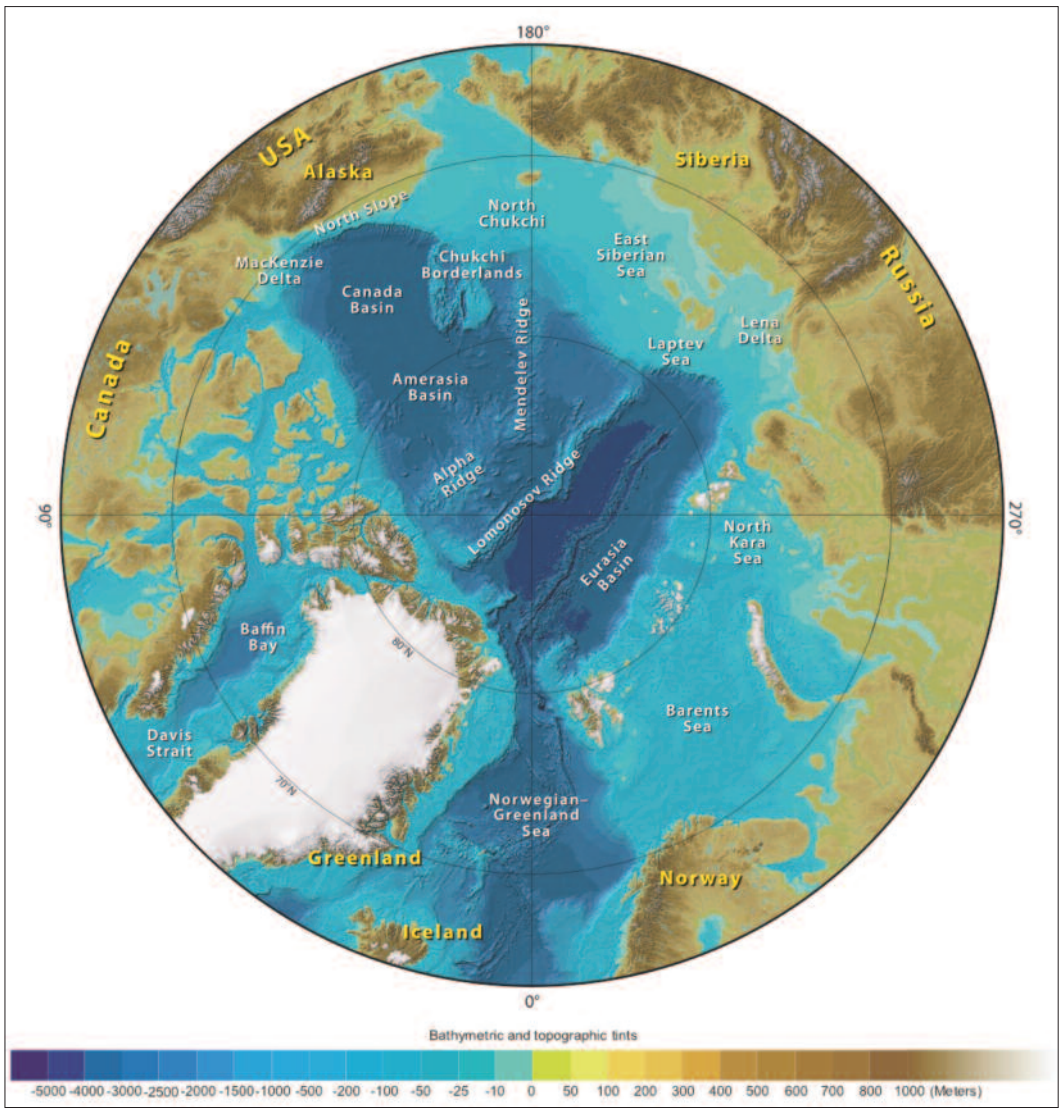


Figure 2 Arctic location map showing bathymetry.

about 5,000km [in diameter, taking] the Arctic circle [as it] runs through the north of Iceland. This is a big piece of the planet, and it looks as if it's an ocean.

Let's just strip off the ice and think about what the geology looks like. Figure 2 shows the 5,000km diameter across the Arctic Circle, so you replicate it across the main countries, the main players: Greenland/Denmark, Canada, the United States (Alaska), Russia and Norway. [These countries are] called the 'Arctic Five'. France and Britain have the idea it should be the 'Arctic Seven', but since France and Britain do not actually have any Arctic coastline, they haven't been invited to join the party, [except] as observers!

Importantly, 50% of the Arctic Ocean under the ice is continental shelf. It's not oceanic crust, it's continental shelf, and [comprises] some of the widest continental shelves on the planet. The map highlights the East Siberian Shelf, the Laptev Sea, the Kara Sea and the broad expanse of the Barents Shelf. You will not find this situation on the passive margins of any other oceans. We like continental shelves because continental shelves have basins, and basins contain oil and gas. So all the elements, for an oil and gas play in the Arctic, are likely to be present. The other thing you can take from this diagram is [that] there are two deep oceanic basins. [There is] the continuation of the North Atlantic ridge, through Iceland, up through the Nansen fracture zone, across the Arctic Ocean and [it comes] to shore in the Laptev Sea, offshore Siberia. The other basin is the Canada Basin. The Eurasia Basin is Tertiary [in date]; the Canada Basin is older — Cretaceous in age. The Canada Basin sits off Canada, Alaska and eastern Siberia.

In terms of working out resources and who owns them a good first pass is the extent of continental shelf. You can see where the continental shelf is, there is already two-thirds of the oil and gas found in the Arctic in Russia and we've yet to find the future resources [— which may be] about the same. The bottom line is it would appear that Russia is going to control the majority of the future oil and gas resources in the Arctic (Fig. 3, *opposite*).

The oil and gas resources

Here [are] the resources. These are big numbers — what do they mean? The USGS think [that] 114 billion barrels of oil, 2000 tcf (trillion cubic feet) of gas are going to be found in the Arctic and I've no reason to disbelieve it — 114 billion barrels of oil [is] probably the amount of oil that's been discovered on the UK and Norwegian sides of the North Sea combined. [The UK and Norwegian discoveries] — two thousand trillion cubic feet of gas [has] kept us going in oil and gas for the last fifty years. That's as much gas as you'll find in the Middle East. I think the [Arctic] oil and gas phase split should be slightly different, but it will still be a lot and it's somewhere between a quarter and a fifth of what we will probably find on the planet over the next 30 or 40 years. Put it another way, it will probably buy us another 30 or 40 years before we have to discover a new energy source, from nuclear fission or fusion to clean coal — i.e. burning coal but [without putting] CO_2 into the atmosphere.

This is how it's distributed (Fig. 3a). The deeper the green, the more oil. [The USGS think there is a lot of oil off the United States.] Well, there probably is, but where they've got it wrong, I think, is [that] there is an awful lot off East Greenland, rather a lot in the Barents Sea on the Russian side (west of Novaya Zemlya) and a great deal in the South Kara Sea. This is where Exxon Mobil are drilling their well [pointed out on PowerPoint slide]; and this kind of pale colour, through the east Siberian sea, [is] probably an underestimate. The East Siberian Sea has a diverse set of basins, and potentially lots of oil and gas, The USGS picture for gas is similar (Fig 3b). The only difference is that the USGS believe there is a lot of gas in the Barents Sea, and a lot of gas in the South Kara Sea. The work we've done — me, the students and previously British Petroleum (BP) — [indicates

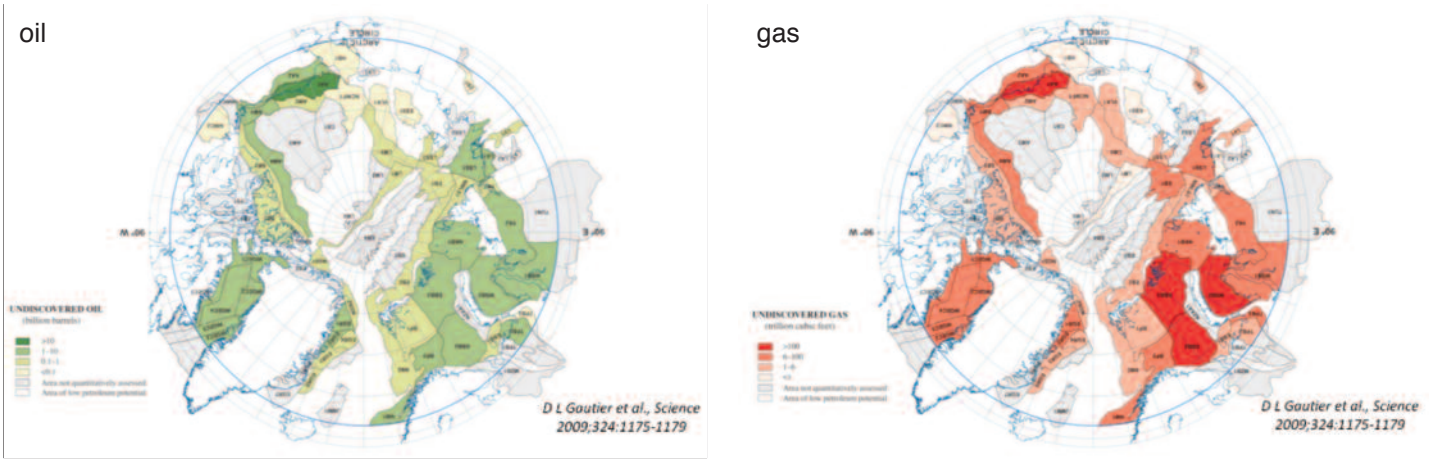


Figure 3 USGS Circum-Arctic Resource Potential.

that] this is going to be oil, not gas, [which is] why Exxon-Mobil are out there.

[Some] history on the Arctic. Here is one of my favourite maps of the Arctic (Fig 4). It is amazing to think that in 1595 Mercator — famous for the lovely Mercator projection, based on the Equator — actually had a go at a map of the Arctic that looks particularly good. You would not really change Alaska and Canada, [but] Greenland could have been better. [He] got the coasts of Norway and Iceland nicely, not bad in east Siberia; but this here, Crockerland [pointing], is of course pure fiction. And at that time there was no melting ice, the icecap was there, nobody knew what was under the polar ice and people assumed, just like Antarctica, [that] it was a continent, or at least Mercator did. Apart from that it's a pretty good early attempt.

Fridtjof Nansen's claim to fame is that in 1895 he really did get as close to the geographic North Pole as anybody. Unfortunately, he didn't quite get there, his boat, the *Fram*, got stuck in the ice from 1895 onwards. He got to 86˚ 14', but then had to retreat back down to Svaalbard (actually Franz Josef Land). The person we accept probably did get to the Arctic was an American called Robert Peary. Now, Peary did some great things, but he often made some fatal mistakes. An American naval officer, he took some Inuit with him and some other Americans, but he forgot to take one important person, particularly if you're looking for the geographic North Pole — he forgot to take a navigator. So the [British] [lambasted his] claim [to] having found the North Pole for some 70 or 80 years, until it was actually a British explorer, Tom Avery, [who] about ten years ago recreated [Peary's] journey with dogs and old[-style] sleds, and did it in about five hours less than Peary claimed, [so] it looks as if [Peary] actually did do it. So I'm afraid the Americans got to the North Pole first. Unfortunately it's the bit above the ocean he got to — [and] the Russians have another view about who owns the North Pole.

The Lomonosov Ridge, running as a positive feature through the Arctic Ocean, separates the Tetiary Eurasian oceanic crust from the Cretaceous Canada Basin or Amerasian oceanic crust. The Lomonosov Ridge is most definitely a piece of continent *c.* 4,000m below sea level. This [area] was recently visited by the Russians, who planted a flag on the Ridge claiming the Arctic for Russia. The North Pole, as shown on this map, sits right on top of the Lomonosov Ridge and you can see the Lomonosov Ridge is conveniently attached to Denmark, Russia and Canada. Hence the dispute over ownership.

There have been operations in the Arctic since the late [19]60s. [They] started in Arctic Canada. Figure 5 shows an ex-BP Chief Geologist, David Jenkins, carrying out some early fieldwork in the North Slope and Brooks Range of Alaska. This, as I said, was my first overseas assignment with BP. The rig photo is a well out on the Arctic Ocean on an island called Reindeer Island. The site was accessed [by] an ice road. You can see the amount of energy that is being used and you can see some other photographs here — this is Dome Petroleum, trying to drill wells in the Canadian

Figure 4 Mercator's map (1595).

Figure 5 Arctic operations.

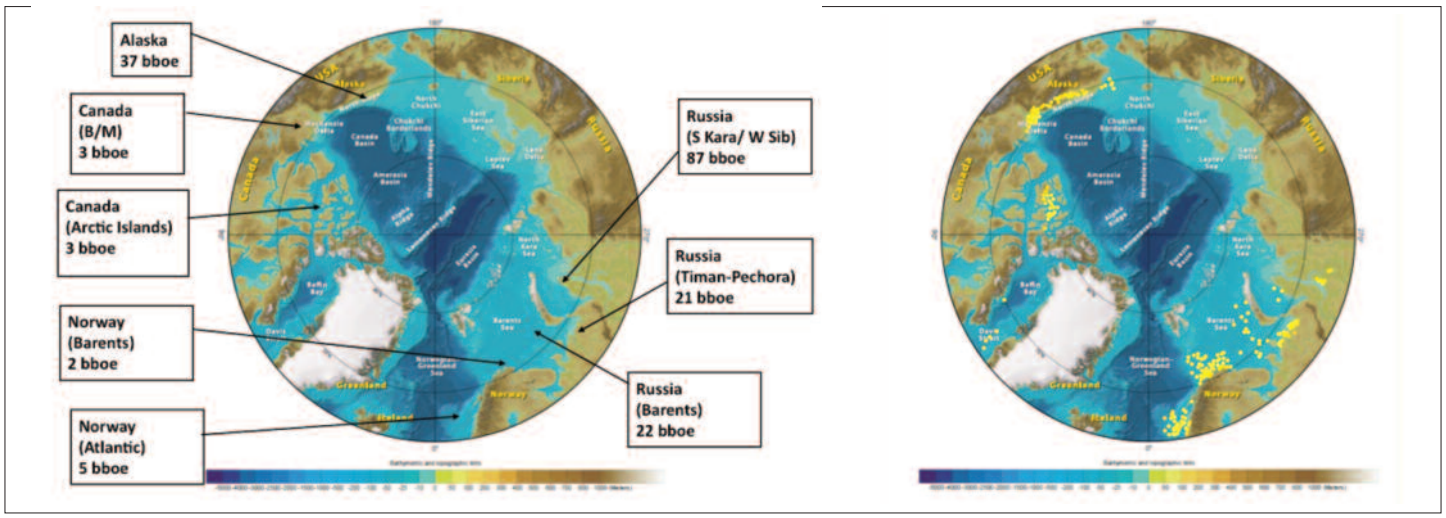


Figure 6 Arctic discovered reserves and exploration drilling.

Beaufort Sea and you can see the ice. They had to put the rig on an ice-breaker to get there. It's a very harsh environment and all caused by the ice, the cold and long winters without daylight.

Let's [look again at] the ice story shown in Figure 1. It shows two diagrams for Arctic sea ice extent. First is from late summer — this is from about September. There is always a bit of lag with respect to the calendar in terms of where maximum and minimum ice is. This is very like what it was in 2014. This ice is receding, temperatures around here in Alaska and Canada have probably risen about 4˚C in the last 50 years. The temperature rise is impacting the Arctic more than anywhere else — [the rise is] probably half a degree at the equator — because the Arctic has a feed-back effect. It heats up the ice, the ice melts, there is more ocean, the sun comes out, heats up the ocean, more ice melts, there is less ocean. It is possible [that] in 20 years, for the first time ever, in the summer we will not have ice in the Arctic from the North Pole. That will make the headlines. The industry I was part of for [more than] 30 years in terms of exploring for [the] oil gas and carbon we produce has actually been responsible for [creating] relatively easy access to the Arctic Ocean, particularly in the summer. The Barents Sea is ice-free year-round — that's why the Russians had their submarine bases at Murmansk and Archangel. The South Kara Sea is ice-free in the summer — that's why Exxon Mobil are in there drilling in this summer's weather window. They've got three months to do it, or they'll never get their rig back until next year. In the summer the east Siberian Sea, the Laptev Sea and the Chukchi Sea are ice-free. [And] ice is also retreating throughout the whole of the Beaufort Sea and through the Sverdrop Islands; this is the Northwest Passage [pointed out on map]. The Labrador Sea and East Greenland are also ice-free.

Access problems

Now, here's the problem [with the] winter ice picture — all [that is] left ice-free is the Barents Sea. You could explore in the Barents Sea as if it [were] the North Sea. The Gulf Stream is keeping the ice away even in winter, but everything else is inaccessible because of the ice. [The ice is] sitting above continental shelf, which has more than 50m of water. We currently have no technology for extracting hydrocarbons under ice in such water depths. We can drill in the summer when the ice is not there, but extracting hydrocarbons is a 12-months a year business.

A further problem is [that] the [Arctic] ice rotates; it does not sit still. So if it is there one day, I can assure you that with the ice moving at 3m an hour, it can be up to 100m away next day. So [there are] real problems with mobile ice, and of course it [also] throws out icebergs — as the *Titanic* found. [So our] facilities, platforms [and] rigs come under the same pressure as the poor *Titanic* did in 1912. Man-made steel structures do not survive well and large lumps of ice the size of double-decker buses are coming at you from all directions.

Now on to [the geology of] the oil and gas. Most of the existing oil and gas fields sit in northern Russia, the north of Siberia (Fig. 6). [There are] oil fields in the Canadian Arctic islands; [and] then Prudhoe Bay is the last in North America. There [are] *c*. 200 million barrels of oil (equivalent) in the Arctic oil here, about [twice as much as in] the North Sea, and most of it sits in Russia. But there [are] few wells — the yellow dots on the adjacent map are the exploration wells; you can see [that] where people have drilled they've found hydrocarbons — where the industry has drilled largely because they are regional source rocks for the hydrocarbons, throughout the Arctic Ocean. Off Norway there are a few wells in the Barents Sea, but from the Kara [Sea] to the Chukchi Sea there is not a single well for [more than] 5,000km. There are broad continental shelves offshore Russia. There are many wells off Prudhoe Bay, Alaska, and [in] the Mackenzie Delta in Canada. But elsewhere [there is] really sparse drilling, sparse seismic data. So, what do we use for data? We go back to basics — we start using gravity and magnetic data again. This is really useful basic original data.

The base to Figure 7 (*opposite*) is a gravity map compiled for the Arctic by the Arctic Gravity Project (2008). [If you] pick out Greenland, Alaska, the peninsula of Novaya Zemlaya and the East Siberian Shelf there are several key [points] to take from this diagram. We can see the North Atlantic Ridge, passing through Iceland and spreading north. It is offset along the massive Nansen Fracture Zone — one of the great straight lines on the planet. [There is] a major strike-slip (or transform) fault similar in nature to the San Andreas Fault in California. It crosses the Arctic Ocean and makes landfall again in Eastern Siberia. We can also see the Canada Basin — you can just about make out the ridge running through the basin, then it is lost under a complex area in the central Arctic Ocean known as the Alpha and Mandelaev ridges. This is the area [under international dispute]. Does that ridge — [the]

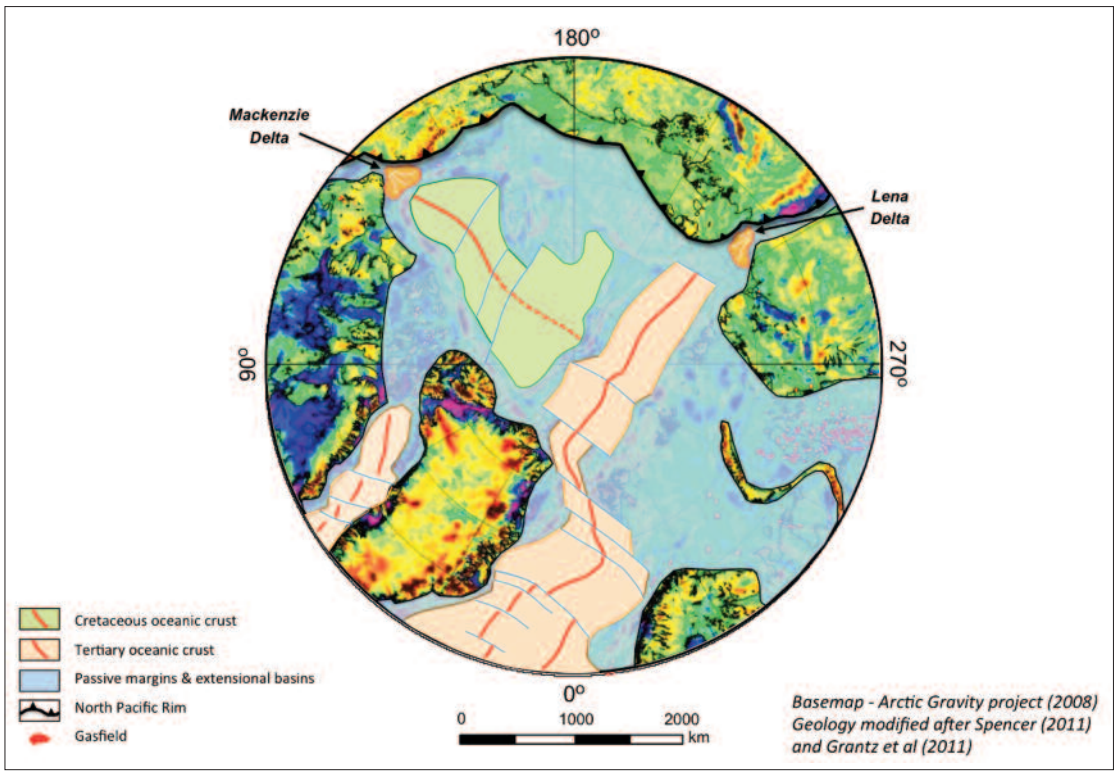


Figure 7 Arctic gravity and structural provinces.

Canada Basin ridge — continue to the Lomonosov Ridge, or is it stopped short by another spreading ridge linked to the Labrador Sea? I believe [that] it is more complicated; I don't think we can take the ridge all the way. [In any case], it is all oceanic crust and we are not going to find a lot of oil and gas on oceanic crust — but we need to know it's there.

We know where the oceanic crust is, [so now] look at the continental crust, as that is where we are going to find oil and gas. I have added the geology on top of the simple magnetic gravity map. The map summarises the geology of the continental shelf areas in the Arctic — the blue representing the passive margins and associated rifts. The oceanic crust of Tertiary and Cretaceous age is shown in green and orange shading; it is interesting from a geological point of view, but not if you want to find oil and gas. The blue areas are the passive margins, including the precursor rifts and the subsiding margins to these oceanic basins. We know [that] a lot of oil and gas is found in passive margins. [For example,] you [may have] heard a lot about Brazil, Angola, offshore Australia, offshore India — these passive margins tend to have a lot of oil and gas and there are a lot of [such margins] in the Arctic — all the yellow area. [The] industry will be drilling [in Greenland] fairly soon. Drilling has already taken place in the Beaufort Sea and in the Mackenzie Delta, and there may soon be some drilling off Norway and Svaalbard.

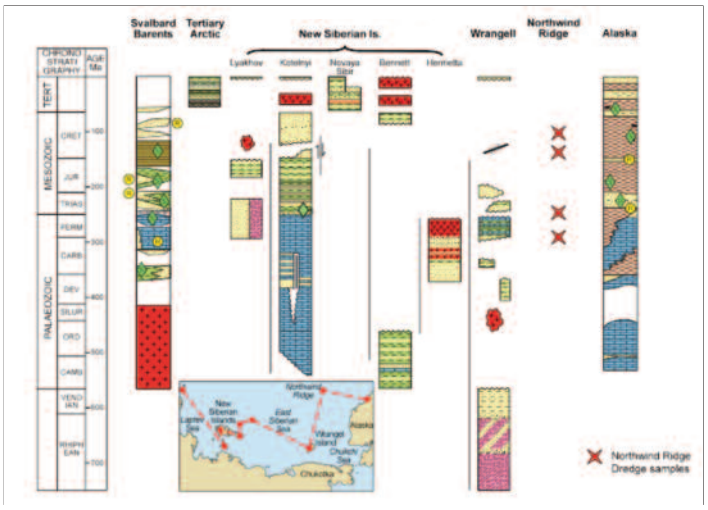
Landward of the passive margins sit precursor rift basins and it is these rift basins that go right back [in age] to the Palaeozoic. There [are] a few thrust-fold belts as well and I have included some 2D seismic examples from the Brooks Range offshore Canada and Alaska.

Territorial disputes

If you're an oil and gas explorer, this is the treasure map — [it] points to the sweet-spot areas for oil and gas exploration. [There are] a lot of places to go looking, most of them clearly in Russia, but [also] a lot of [other] places to search. And one last thing — [there are also] two spreading centres, two oceanic ridge tip-lines and the two largest deltas in the Arctic situated where these spreading centres intersect the continent. The Lena Delta in the Laptev Sea is probably the largest unexplored delta in the world. It is a beautiful Arctic delta with thermokarst lakes and permafrost; and then [there is] the Mackenzie Delta offshore Canada, which has already yielded significant quantities of oil and gas. It is classic source to sink. There is a ready source of sediment in the hinterland and a deep hole in the ocean. The sediments have exploited this relationship and built up almost 15k of Tertiary sediments in both of these areas.

Figure 8 [is a] regional stratigraphic diagram [that] presents the evidence for a continuous slab of continental crust running from the undrilled Kara Sea to Alaska. The data is presented in the form of a chrono-stratigraphic correlation that runs from Alaska, [to] almost as far as the Barents Sea. The line runs through the offshore East Siberia and is a combination of well data from drilling and outcrop samples from the Arctic islands. As geologists we like doing a bit of fieldwork when we can. There is also some additional data from dredge samples from the Arctic shelf. There is a lot of geology here, but the key observation is that this is essentially a single, contiguous continental plate, which the USGS has largely ignored. In the Barents Sea a Permian carbonate platform is overlain by a major marine transgression, which is the key source rock in the area. The later geology is largely deltaic. Near the Siberian islands the Permian carbonate platform is overlain again by a major Triassic [marine] transgression and

Figure 8 Arctic chrono-stratigraphy.



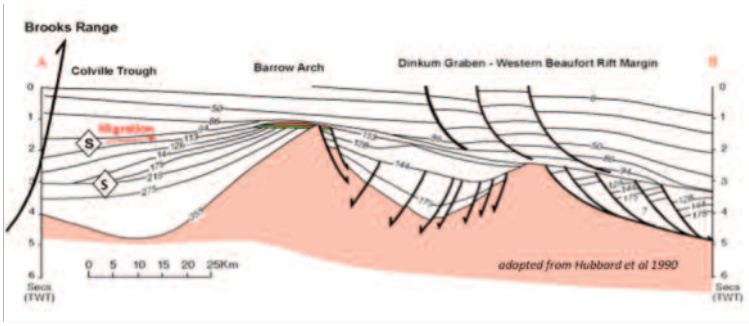


Figure 9 Regional cross-section of Alaska.

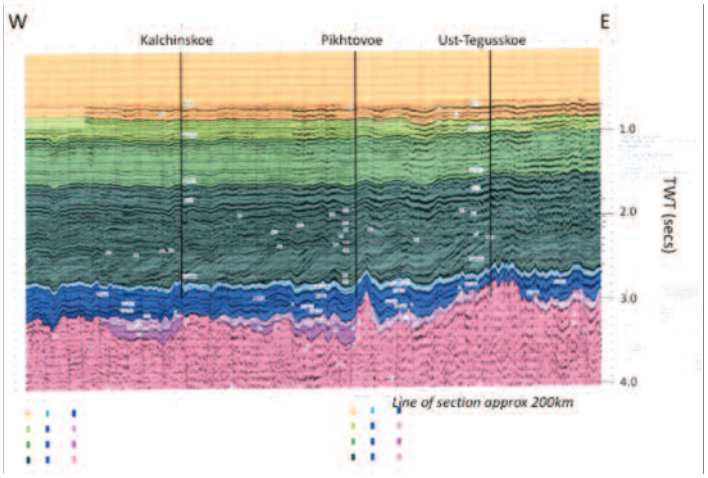


Figure 10 Regional seismic line across Western Siberia.

then [by] deltaic [sediments] and volcanic [deposits]. In Alaska and some 5,000km distant, the Permian carbonate platform is yet again overlain by a marine transgression, represented by the Shublik source rock followed by deltaic sediments. These are actually the molasse deposits forming the Colville Delta, sourced from the emergent Brooks Range to the south. In summary, the same geology is observed over a strike distance of 5,000km — it's the same plate, on the same scale as Arabia, one big carbonate platform forming these Arctic shelves.

Figure 9 shows what Alaska looks like in section. [The] line is more than 700km long. This interpretation is based on a regional seismic line from across the narrow North American continental margin. The main source rock intervals are highlighted. [There] is a big thrust fold, [and] the source rocks sit on the foreland of the thrust-fold belt. This large high formed by the flexural bulge in the north forms the biggest oil field in North America — the giant Prudhoe Bay field.

But the real prize is going to be in Siberia. Figure 10 [shows the] west–east line crossing West Siberia, roughly 200km long. The light blue horizon is the Bazhenov source rock. This is from the onshore West Siberia Basin. [It is] the same source rock as we have in the North Sea — it goes all the way through the Norwegian–Greenland Sea and Barents Sea, around to western Siberia. In the North Sea it is called the Kimmeridge Clay; in Russia it is [known as] the Bazhenov. However, it is exactly the same and it is as rich — it [will] produce a lot of oil. These prominent seismic reflections sitting on top are wonderful pro-grading deltas. These are known as clinoforms and they represent the delta moving from east to west across the West Siberia Basin from the emergent East Siberian Shield. The majority of the oil and gas sits in west Siberia on top of these deltas. [They are] probably the largest single petroleum system on the planet, bigger than any single system in the Middle East. It is only because the Middle East has multiple systems in Arabia, Iran and Iraq that [makes it] a bigger overall province.

[These deltas are thought to hold] 400 billion barrels of oil equivalent. That is why Russia supplies and controls an awful lot of oil and gas into the Western European market. The data offshore is very similar. Importantly, the Bazhenov source facies is still present in the offshore. Also, the westerly pro-grading clinoforms forming the deltas are still present offshore, as is the delta top where the reservoirs are predicted to be. It is exactly the same as the onshore basin, so if you have 400 billion barrels of oil equivalent present onshore, [and] there is about a third of the area of the basin offshore, there is going to be a significant amount of oil and gas, a spectacular amount of gas and oil. [On] the other side of Novaya Zemlaya — into the Barents Sea — is the Admiralty Arch in the eastern Barents; and the Uralian thrust-fold belt, [which] hasn't been drilled. Next is a giant gas field Shtokman, which sits in the central Barents. It is not producing yet due to lack of commerciality — nobody needs much gas north of the Arctic Circle.

The geology and palaeogeography

As geologists, when we want to find good source rocks, we use gravity and magnetics — we resort to a bit of fieldwork and we also rely heavily on plate tectonic models. Where was the Arctic in the late Palaeozoic? [Ron Blakey at the University of Arizona has produced the palaeogeography maps in Figure 11, *opposite*.] You will recognise a reunited Pangea supercontinent comprising Gondwana in the south and Laurasia to the north. Eventually there [developed] major suture between Africa and South America, which [formed] the South Atlantic. This is the Variscan and Caledonian fold band; here is the Arctic [pointed out on the PowerPoint slide]. [Along] the Andean margin off South America — this is back in the Permian 260 million years ago — there [was] still subduction of the Pacific plate, [and here, at] what would be the Aleutian Islands [today] there is subduction of the Pacific plate off Alaska. Nothing has really changed despite all the plate movements round the planet. The Arctic Ocean, at least the Pacific rim of the Arctic Ocean, has not changed much since the early Palaeozoic.

Now, it is [at] this large epicontinental sea behind the chain of what were presumably (and still are) volcanic islands, [that] we think [there was] regional anoxia. We think this is the Triassic Shublik marine transgression that has given us these regional oil and gas source rocks. They are just like the source rocks we see later in the Jurassic in the Middle East, on top of the extensive Triassic carbonate platform there. It is a very similar setting [throughout] this whole area right through from what is now Alaska to the Barents Sea, right through to East Siberia. [This is where] you would predict the source rock to be present.

How about the Jurassic? Look closer to home. The Kimmeridge Clay in Dorset used to be mined for mineral oil. You can follow that epicontinental seaway all the way into the Arctic and right round into Western Siberia. The Bazhenov source rock [is] a large epicontinental, highly anoxic sea; and you could argue [that] there is anoxic present in the Oxfordian and also in the Lias, but certainly in the Kimmeridgian it's quite superb. So that whole area there has potential for world class Upper Jurassic, Kimmeridgian source rocks, right through the Norwegian–Greenland Sea and Baffin Bay, and potentially as far

Figure 11 Arctic palaeogeography maps (reconstructions by Ron Blakey, NAU Geology, University of Arizona).

south as the northern part of the Labrador Sea — still to be explored. [There are also] some Tertiary source rocks.

If you're a petroleum geologist like me, this is the type of basin you love to see, not just one source rock, but multiple intervals providing backup. Essentially lots of potential, lots of different petroleum systems and [it was only in] this [period [that] the Arctic Ocean [was] actually a closed ocean. [The geologist] Jonathan Bujak [has] convincingly demonstrated [that] there was a period of warm Arcitc temperatures and a freshwater layer on the Arctic ocean as a result of freshwater river runoff leading to a well documented Azola flood at this time. Azola is a freshwater fern, a very greedy fern [that] doubles its biomass in two or three days. This [was] at the time of the Palaeocene–Eocene thermal maximum, the last time [that] there was as much CO_2 in the atmosphere as there is now. According to Bujak [Azola] fern actually gobbled up the excess CO_2. As you know, ever since the Eocene this planet has been in icehouse conditions, with polar icecaps; [but in the Palaeocene–Eocene there were no polar icecaps.] You could probably have sunbathed on the margins of the Arctic Ocean.

The production technology

How do we produce any discovered oil and gas from the Arctic Ocean below the Arctic ice? Here is one of the more imaginative ideas. Vladislav Navin, who was working for Gazprom in Russia, came up with the sub-sea (and sub-ice) nuclear-powered production facility concept. Now here's the problem: We're in the Arctic, icebound for six months of the year, [the] ice is thick [and] sits on water up to 200m deep. You can't build an artificial island [as] we did in Alaska. How on earth do you get from the surface of the ice to the oil and gas on the seabed? That's what you've got to do, that's the key engineering problem in the Arctic. Basically, you have to take the ice out of the equation, so this is what Navin did. Not only will we [drill] for oil and gas in the Arctic, we're going to use a nuclear-powered submarine to do it! [Navin's idea] mixes nuclear power with the potential for oil and gas leaks. I'm not joking — [the idea] is in the public domain! This is what Gazprom considered for the Leningradskoye development!

Somehow you have to take the ice out of the equation and you have to connect the oil and gas to pipelines along the seabed to the land. [There are] all sorts of problems with ice-flow, all sorts of problems with permafrost, [so] basically we still do not know how to do this — yet people are [already] drilling wells. Why are Exxon drilling this one now? If they find anything, they can't do anything with it. We'll have a think about that later. [At the moment we do not] know how to produce oil from under more than 25m of water under ice. It's scary stuff. However, at Imperial College we think they can come up with better ways, but this is 30, 40, 50 years in the future. At the moment if we produce oil from a well and take it to the surface, we either put it in a tanker, a train or a pipeline and we take it to a refinery, and the refinery takes the oil — which is a mixture of all sorts of crude products — and turns it into products that we can use, [such as] petrol for our cars, hydrocarbons for plastics [and] all sorts of chemicals. But what if we could actually do the oil refining in the well — essentially put the refinery in the production well? If we actually put [the refining process] down the borehole we would never actually see any of the nasty CO_2 emissions from the refinery, [or] any CO_2 emissions from transportation. You actually produce the refined products (ideally pure hydrogen) down the hole, so all the nasty by-product stays in the ground.

It is 'blue sky' technology, years away from implementation at industrial scale, but it is working on the lab bench. The test bed for [this technology] is working, [and] at the moment we are getting methane at the surface — a lot cleaner than crude oil. Ultimately, maybe in 50 years time, we will be producing hydrogen — raw hydrogen, raw energy. Now, we like burning hydrogen, don't we? Hydrogen plus oxygen equals water! That's the product of burning hydrogen. But it's a long, long way off.

The politics

Now for the next problem: politics. I would argue that the geology is fine — we are going to find lots of oil and gas in the Arctic. The technology and the politics of who owns and regulates activity in the Arctic will be the real issues. So who are the interested parties? One of my ex-colleagues, Dr Brian Lovell at Cambridge, calls the various protagonists 'tribes', because that's how he felt they behaved.

The tribes, their interests and the key drivers can be summarised as follows:

- governments — see energy security and the next election;
- indigenous peoples — see nature as resources needed to survive;
- environmentalists — [see the] Arctic as a pristine wilderness;
- oil companies — are driven by short-term shareholder value and demands.

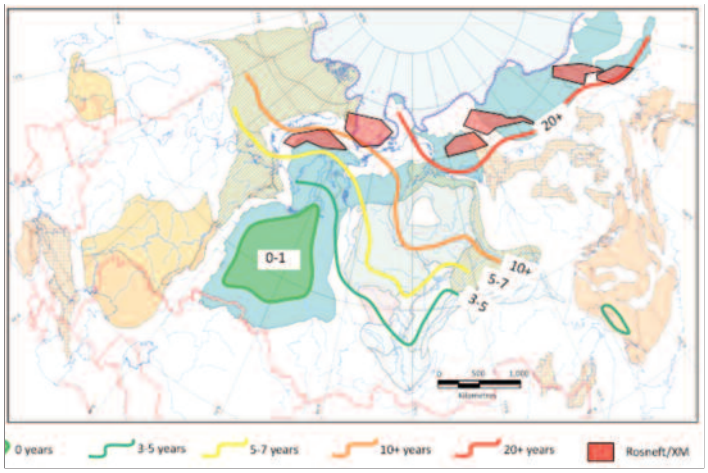


Figure 12 Russian Arctic — timing of potential production.

Governments tend to be driven by the next election and a focus on vote-winning policies.

The Arctic has four million people living and working [in it, of which] 15% are actually indigenous peoples. It is not like the Antarctic, which is a continent surrounded by an ocean — [the Arctic] is an ocean surrounded by a continent, and continents that have had people living and working on them for thousands of years.

The environmentalists that see the Arctic as a pristine wilderness, which is what you experience when you step off a plane in Alaska — it is beautiful. As for the oil companies, they are driven by shareholder value [and] keeping that share price up. It is very difficult to get these conflicting interests to come together.

There [are] also numerous boundary disputes. Take the example of Hans Island, possibly the most unfortunate island in the world. It sits on the boundary between Denmark and Canada in Baffin Bay, and, importantly, ownership of the island brings with it control of the bay. Every six months both countries re-stake their claim to it. Just to claim it, a senior politician from each government flies out and makes a speech and then flies back again! [Another example is that] the USA and Canada cannot agree on the boundary in the Beaufort Sea. They blame the British and the Russians — the British who used to administer Canada and the Russians who used to own Alaska. But basically it is down to the [International] Law of the Sea. The Canadians would love to take [their claim] straight to the North Pole. However, the Law of the Sea says [that ownership] should be coast-parallel, favouring the USA. A bit of the issue here [is that] the [US Government] has not signed the Law of the Sea, but are still claiming [the ownership].

Now to flags. The main one [was planted by] two Russian submariners, [who] went down 4,000m to plant [a titanium Russian flag] on the North Pole on the Lomonosov Ridge. The Canadian Foreign Minister came right out and said, "This is not the 15th century, you can't just go round planting flags!" [The issue is] still being argued about, and the Canadians are spending a fortune in geophysical research just to demonstrate [that] the Lomonosov Ridge joins Canada.

Finally, Figure 12 [shows] a map of years to production in the Arctic. It was drawn [more than] ten years ago to suggest how fast things would happen in the Arctic. West Siberia is in production now, moving northward along the Yamal Peninsula to the South Kara Sea, where ExxonMobil are [now also] drilling. [When the map was produced,] we predicted [that drilling would start in] about five to ten years and we were about right. This here [on the map] is about 20 years and this is what ExxonMobil have done, with Rosneft as a partner. They have effectively licensed most of the East Siberian Sea. The interesting areas with no drilling [that] I highlighted earlier [are] each individually the size of the North Sea — [and they represent only] 50% of the area.

Concluding remarks

[In summary] we really don't know much about the Arctic yet, certainly not technologically; we don't know how to do it. I firmly believe [that] it is all happening too fast. We really have not worked out how to mitigate an oil spill yet. We didn't know how to do it in the Gulf of Mexico, where the Macondo spill happened. We certainly don't know how to do it in the Arctic, under the ice. I think we ought to sort these things out before we start going into the farther reaches of the Arctic. The Barents Sea is reasonably accessible — we should not complain about the exploration in the Barents Sea. We can take it by small steps into places like the South Kara Sea. I think we do need the resources. There's really nowhere else to get them unless we all make new friends in the Middle East, and that doesn't look too good at the moment. So we do need some backup. However, we do need to slow down and make sure [that the situation is] not used for political purposes.

A coastal tour of Kent's geology

Peter Golding

(Fellow of the Geological Society, WEA and Univ. Kent Tutor)

Abstract

Kent is situated on the northern half of the great Wealdon anticlinorium. As such its rocks dip to the north. The coastal cliffs therefore provide an almost continuous section through Kent's geology. Most of the county lies on Cretaceous rocks, while a relatively thin Tertiary sequence forms the north Kent coast.

Coastal cliffs display an almost continuous sequence of Cretaceous rocks from the non-marine Wealdon sands and clays (continuing just over the border into Sussex) to the shallow marine 'Greensands', which contain our most famous building stone, 'Kent Ragstone'. These sediments are overlain by the Upper Cretaceous Chalk that creates our most iconic landscape, the White Cliffs of Dover.

A small exposure in Pegwell Bay shows the unconformity between then Upper Chalk and the Tertiary sediments, which mark a return to shallow marine conditions. The last major unit is the London Clay with its internationally important plant fossils, exposed in the landslips and mud flows of the Isle of Sheppey.

Kent was never glaciated, but the effects of periglaciation are frequently displayed. For example the Dour Valley, which at the coast at Dover is asymmetric, while beautiful involutions occur at the top of the Chalk on the Isle of Thanet.

Although much of the coast is cliff, Kent has three major areas of Holocene sedimentation: the North Kent marshes, together with the Thames and Medway estuaries; the marshes filling the old Wantsum channel between the Mainland and the Isle of Thanet; and the great coastal embayment containing Romney Marsh.

Coastal changes continue today, exposing even more exciting geology.

[OUGS Canterbury Symposium: Marine Geotales; original transcription by Marian Hastings from the seminar recording; written up by Peter Golding, and edited by POUGS Editor David M. Jones]

Kent's coast is *c.* 200 miles long. The section begins in the Early Cretaceous, so we are looking at 145 million years of geology.

The aims of the talk were, firstly to give a brief account of our geology, as it is exposed along the coast, and secondly, to form a background for the following day's field trips.

The field trips went to Folkestone, to study the Mid-Cretaceous sediments, Samphire Hoe at Dover to look at the Chalk and the Channel Tunnel workings, Reculver, near Herne Bay, to look at Tertiary sediments and coastal protection, and finally, a building-stones walk in Canterbury.

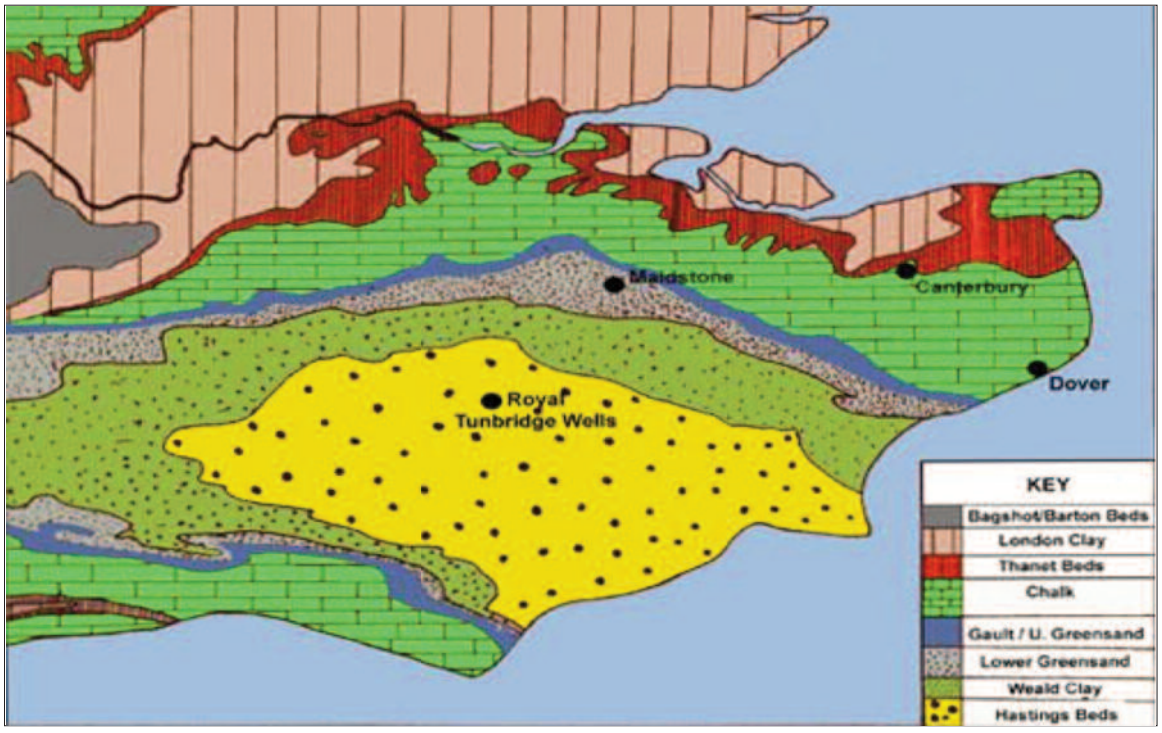
Figure 1 is a simplified geology map of South East England, showing that the bedrock geology is nearly all Cretaceous in age. The early Lower Cretaceous rocks are non-marine, Mid-Cretaceous rocks are shallow marine, while the Upper Cretaceous is represented by the Chalk. Above the major end-Cretaceous unconformity, marine Tertiary sands and clays are exposed along the North Kent coast.

Structurally, the South East is dominated by the Weald Dome. The stratigraphy is very simple. It is the classic layer-cake geology. Dips are very gentle from horizontal to a few degrees.

Strictly, the Weald Dome is an anticlinorium and as such, carries smaller folds on its limbs — hence the Chalk of the North Downs, dipping into the Thames Estuary below the Tertiary cover, reappears as the Isle of Thanet and east of London (*see* Fig. 1).

The earliest Cretaceous rocks were deposited in a landscape very different from that of today. The Weald area was one of low-lying marshes, braided rivers, lakes and ponds, dominated

Figure 1 Bedrock geology of south-east England.



© OUGS ISSN 2058-5209

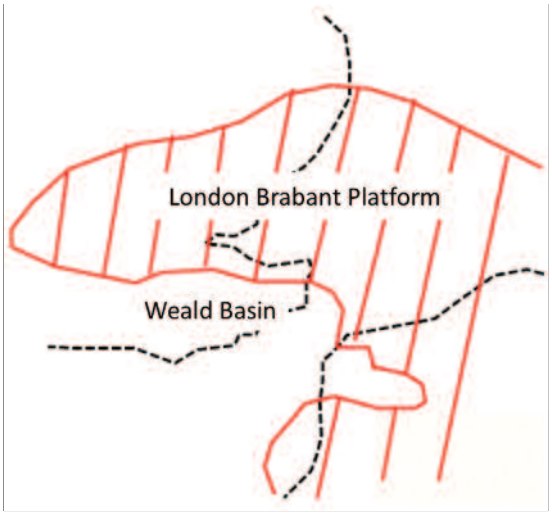


Figure 2 The London Platform in the Weald.

by the London Platform, an upland area to the north, now buried at *c.* 300m below younger rocks (Fig. 2). The platform supplied sediment to a subsiding basin, the Weald basin (Allen 1975). Arenaceous sediments were deposited when it was high and argillaceous sediments when the platform was reduced.

Then, as we move into the Mid-Cretaceous, this freshwater basin was inundated by a shallow sea. This was the environment of the Greensands and indeed slightly deeper water conditions for the Gault Clay exposed at Copt Point, Folkestone.

To see a good coastal section of the earliest Cretaceous rocks one needs to travel just over the county border to East Sussex. There, at Cliff End, Ashdown Sands are exposed in a magnificent cliff section. Wadhurst Clay forms the upper part of the cliff, although its lowest part is developed as a sandstone, the Cliff End Sandstone (Fig. 3).

The section contains features that you would expect to find associated with a river-plain environment. These include: shallow water ripples, river channels, point bar deposits, finely laminated lake sediments, and areas of exposed sand and mud. Upon these, red-mottled palaeosols were developed,

Figure 3 The Cliff End Sandstone, comprising Wadhurst Clay in the upper part and sandstone in the lower part.

referred to by the old geologists as 'cat's brain clay' (Fig. 4). Organisms associated with this environment are preserved as rootlets, plant stems and even tree trunks. Bone beds contain wood, rolled bone, fish teeth and, rarely, dinosaur teeth. Rarer still are mammal teeth. Further evidence of dinosaurs is preserved as footprints.

Eastward, over the county border is the great area of modern sedimentation — Romney Marsh. Strictly, Romney Marsh is the northern part of this area, which silted-up naturally. Roads follow what are obviously old wandering trackways associated with salt marsh channels. By contrast, much of Walland Marsh is a very different ordered landscape, which resulted from systematically enclosing areas of salt marsh and tidal areas, a process known as inning. Rumensea Wall separates the two marshes; and closely associated with the Rumensea Wall is the Rhee Wall. This was an embanked canal constructed to flush sediment from the harbour at New Romney. Today it carries the A259 (Eddison 2000).

Figure 4 Finely laminated lake sediments and areas of exposed sand and mud with red-mottled palaeosols, referred to as 'cat's brain clay'.

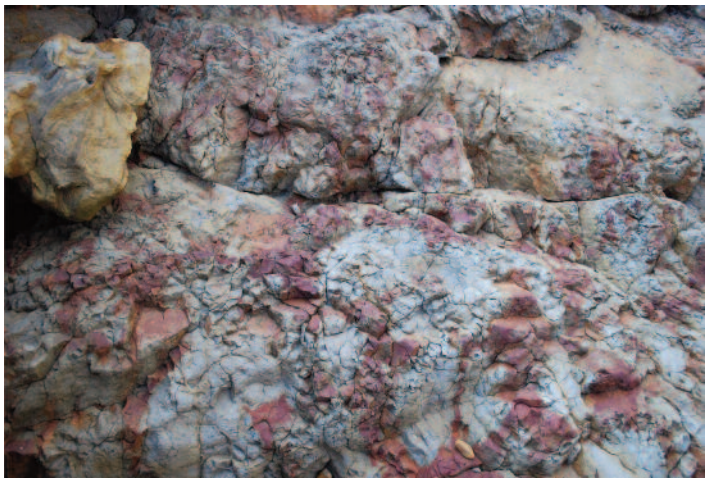


Figure 5 (*opposite*) shows the development of the Rother channel across Romney Marsh over the last 2,000 years. Originally it was thought that the river exited along a northern route near Hythe. However, it has been shown that this 'exit' was in fact a tidal embayment. It was here that the Romans built their fort, *Portus Lemanis*, also known as Stutfall Castle. As the fort was built on the Weald Clay of the old cliff line its walls are now slipped and fallen (Fig. 6, *opposite*) (Hutchinson *et al.* 1985). By the 10th century the Rother exit was established at New Romney, but it was beginning to silt up and this culminated in the great storms of 1286, when the channel was finally blocked. Today stains on the columns inside the church at New Romney mark the height of the inundation (Fig. 7, *opposite*). Subsequently, a new southern exit was established into what is now Rye Bay. At the entrance, the town of Old Winchelsea was established

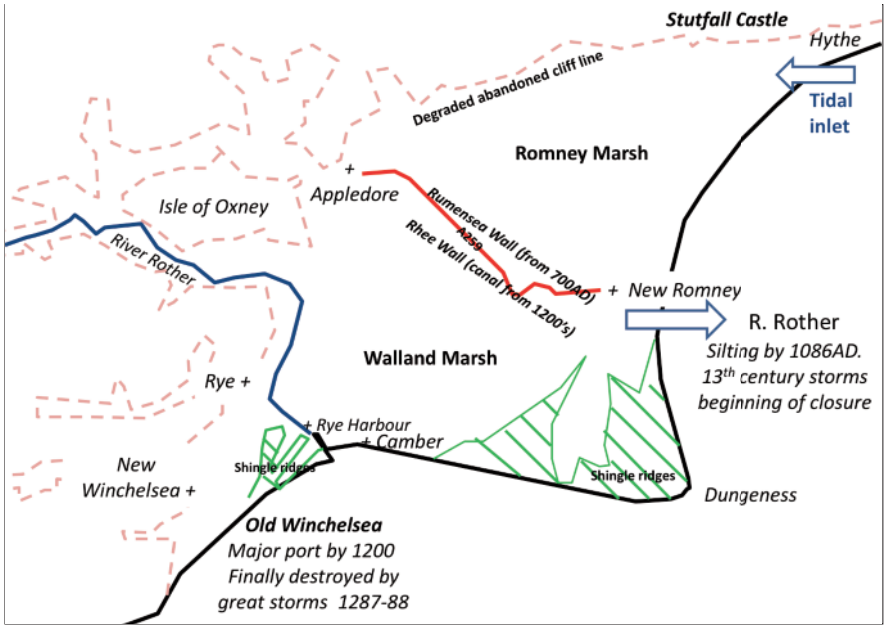


Figure 5 Route of the Rother channel across Romney Marsh.

Figure 6 The Roman fort, Portus Lemanis*, or Stutfall Castle, built on the old cliff line of the Weald Clay.*

Figure 7 Staining on a column in New Romney church marks the height of inundation in great storms of 1286 that finally blocked Rother channel.

on a shingle bank. By 1200 it had grown into a major port, third behind Southampton and London. Old Winchelsea was finally destroyed by the storms of the 13th century and the town relocated to its present position. The Rother now flows to the coast through Rye, to Rye Harbour. (For more detailed illustrations of the development of Romney Marsh and the Rother, see Long *et al.* 2007).

The seaward margin of the Romney Marsh complex is defined by the great shingle cuspate foreland of Dungeness. It is composed of innumerable shingle ridges where longshore drift has steadily built the point in an easterly direction. Natural migration of the point has been halted by the annual removal of shingle and its transfer west to protect the nuclear power station.

Travelling towards Hythe, the abandoned cliff line is formed by the rocks of the Lower Greensand. The base of the Lower Greensand marks the time when the freshwater basin was overwhelmed as a shallow sea transgressed into the area. The sequence begins with the Atherfield Clay, which is rarely exposed. The overlying Hythe Beds in Kent are expressed as the Kent Ragstone. It can be seen in a number of old quarries around Hythe, showing the characteristic rhythms of 'rag' and 'hassock' (Fig. 8, *overleaf*). The rag is a sandy limestone, whereas the hassock is a softer calcareous sandstone. Reefs of ragstone occur on the coast a little farther north towards Folkestone. Here, 'Rag', Kent's iconic building stone was also quarried. Modern marine organisms have bored into these reefs, which makes 'coastal rag' easily identifiable in buildings throughout East Kent. At the top of the rag sequence there is a particularly sandy ragstone, which contains large amounts of the green mineral glauconite. This green, sandy variety of ragstone occurs only in the Hythe area and again if seen in buildings, for example, in Canterbury, it must have originated from this limited geographical locality (Worssam and Tatton-Brown 1993).

The overlying Sandgate Beds, a variable sequence of sands and silts, are also rarely exposed.

East of Folkestone Harbour the cliffs are undefended and expose the youngest sediments of the Lower Greensand — the Folkestone Sands. These are shallow-water marine sands, generally soft, but at Folkestone they contain hard concretionary layers that form a boulder-strewn beach from the promenade into East Wear Bay (Fig. 9, *overleaf*). These are usually referred to as 'sponge rock' because they contain vast numbers of sponge spicules. Recently, dinosaur footprints have been described from the Folkestone Sands, implying that they are, at least in part, intertidal (Hadland 2012).

At Copt Point, the cliffs are formed from the overlying Gault Clay. This is a deeper-water deposit and marks the beginning of a major transgression. It was the time when the London Platform was inundated and buried. It has never been re-exposed. This is also one of the main sites for fossil-hunters in Kent. As the clay is eroded, fossils such as ammonites, belemnites,

Figure 8 Characteristic 'rag' and 'hassock' quarry exposure of Kent Ragstone in the Hythe Beds.

Figure 9 Hard concretionary layers and boulder-strewn beach of the Folkestone Sand (youngest sediments of the Lower Greensand) east of Folkestone Harbour.

bivalves, corals, crabs and, rarely, vertebrate remains are washed out and easily collected.

The top of the Gault Clay marks the end of the Lower Cretaceous. There is a small break where the top of the Gault is burrowed and then overlain by the oldest bed of the Chalk — the Glauconitic Marl. This can only be seen in landslips associated with Folkestone Warren. There the Chalk and Gault Clay have moved on the upper surface of the Folkestone Sands. This has led to a complex of chalk falls and slipped masses, movement of which continues intermittently today.

Beyond the Warren towards Dover the marly Grey Chalk Subgroup is exposed at the base of Abbot's Cliff. These grey chalks characteristically contain hard limestone bands, separated by marl beds, which can contain up to 50% clay. The next major feature towards Dover is Samphire Hoe. This area enclosed by sea walls was built to contain spoil, mainly the Chalk Marl, from the Channel Tunnel workings (Fig. 10). Subsequently, the spoil has become vegetated and now carries a variety of wildlife, especially, in the spring the rare early spider orchid (*Ophrys sphegodes*). It also provides an ideal site to view marker beds in the Chalk. Towards the top of the Grey Chalk, the 'scratch bed' (Jukes-Browne Bed 7) is clearly exposed. A prominent slot in the cliff face marks the site of the Plenus Marls, which lie at the base of the White Chalk Subgroup (Fig. 11, *opposite*). The upper part of this lowest division is a typically flintless, nodular chalk known as the Melbourn Rock; together these are the Holywell Nodular Chalk Formation (Mortimore 1997). Continuing towards Dover, the northward dip steadily brings younger chalks into the clifftop.

Dover town is situated in the Dour Valley. This is a superb example of an asymmetric valley. The south-west-facing slope is much steeper than the north-east-facing slope. Asymmetry results from periglacial processes (Fig. 12, *opposite*). Just beyond Dover there is the famous Langdon Stairs that gave access to the base of the cliff. The Chalk sequence exposed in the stairs has been carefully mapped (Mortimore 1997), but a recent cliff fall has made this inaccessible for the foreseeable future. Along the coast the Chalk is strongly jointed. Cliff falls occur from joint surfaces. Just beyond Langdon Stairs a large area of cliff is set down between two joints and has moved seaward such that a deep graben structure has developed at the back of the block (Fig. 13, *opposite*).

Northward, beyond Deal, Holocene sediments fill the old Wantsum Channel, which once separated the Isle of Thanet from the mainland. This was still a seaway in Roman times, with Richborough Fort (*Portus Rutupiae*) at its southern end and the Reculver fort (*Regulbium*) at the northern end.

The Wantsum Channel lies within the Richborough syncline, filled with Tertiary sediments. Their unconformity with the Chalk is exposed in the degraded cliffs on the northern

Figure 10 Sea walls built to contain the Chalk Marl and other spoil from digging the Channel Tunnel.

side of Pegwell Bay (Fig. 14). The Tertiary sequence begins with glauconite-coated flints of the 'Bullhead Bed', which is overlain by a sequence of clays, silts and sands known collectively as the Thanet Formation (Shephard-Thorn 1988, 26–7).

The Chalk of Thanet is formed into a gentle monocline with its steepest limb on the southern side (Shephard-Thorn 1988, 31–2). Following the cliffs towards Ramsgate, the southerly dip brings zones of progressively older Upper Chalk above beach level. Throughout Thanet, periglacial freeze and thaw has created a layer of shattered chalk visible at the cliff top. These are overlain by spectacular involutions in superficial deposits (Fig. 15, *overleaf*).

Beyond North Foreland the coast swings westward. It is here, around Foreness Point, that the youngest Chalks of Kent are found (Zone of *Marsupites testudinarius*). Inland, there is an old quarry in slightly younger Chalk (Zone of *Offaster pilula*).

Westward, leaving Thanet, the Wantsum Channel is again crossed and beyond the Reculver Fort lies a continuation of the sequence seen in Pegwell Bay. The unconformity with the Chalk is not exposed here, lying some 20m below beach level. These two sites are the type strata for the Thanetian Stage of the Palaeocene. The cliffs contain a marine sequence of fine, silty sand (Thanet Formation and overlying Upnor Formation), a pebble bed (Harwich Formation) and clean-washed sands (Harwich Formation). The cliffs are topped by the basal beds of the London Clay (Fig. 16 *overleaf*) (Ward 1978).

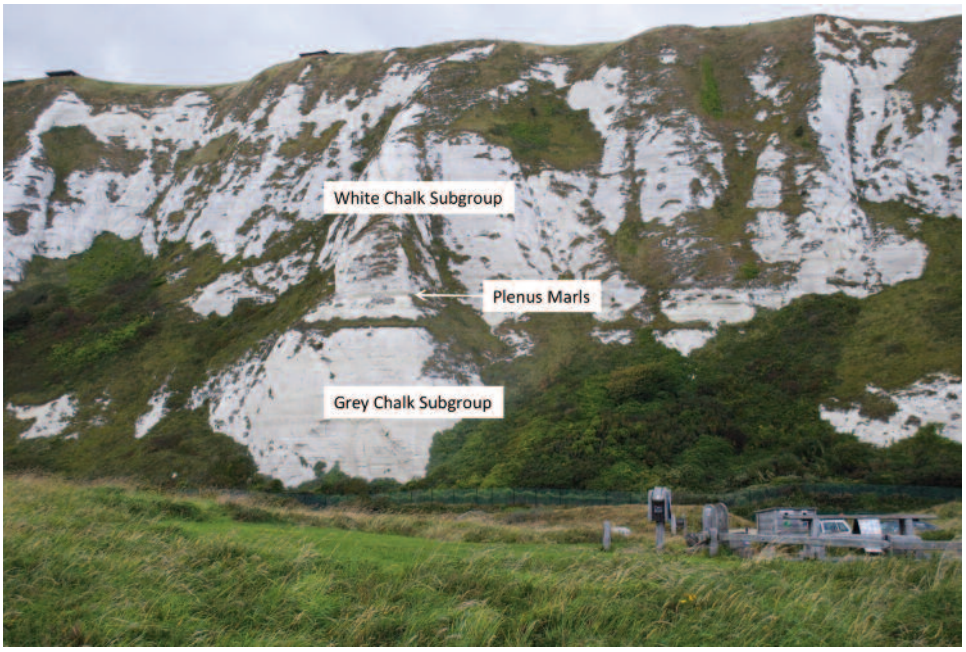


Figure 11 The Plenus Marls at the base of the White Chalk Subgroup.

Figure 12 Asymmetric Dour Valley from periglacial processes.

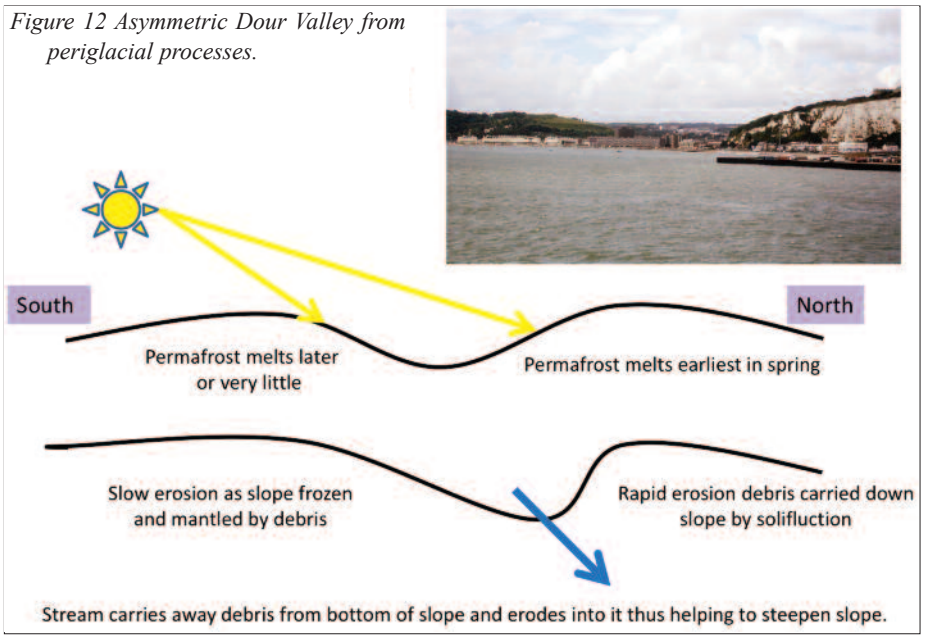

South
North
Permafrost melts later or very little
Permafrost melts earliest in spring
Slow erosion as slope frozen and mantled by debris
Rapid erosion debris carried down slope by solifluction
Stream carries away debris from bottom of slope and erodes into it thus helping to steepen slope.

Figure 13 Incipient cliff fall north of Langdon Stairs.

Figure 14 Unconformity of the Richborough syncline Tertiary sediments with the Chalk.

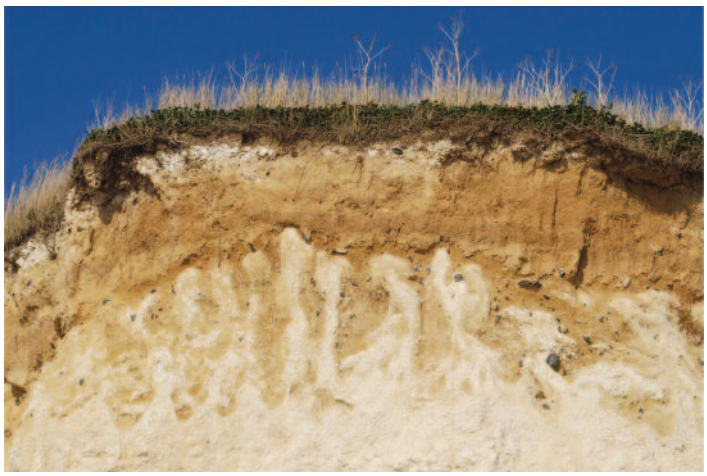


Figure 15 Shattered Upper Chalk above beach level in Thanet, caused by periglacial freeze and thaw, and overlain by spectacular involutions in superficial deposits.

Westward, beyond Bishopstone Glen to Herne Bay, the London Clay is obscured by sea walls and grading of the cliff. Further exposures of London Clay can be seen in the long section on the Isle of Sheppey between Minster and Leysdown. This is the other major fossil site in Kent. It is internationally famous for its plant fossils, but it also contains a diverse vertebrate and invertebrate fauna.

Along the north Kent coast, the London Clay essentially marks the end of the solid geology.

The Isle of Sheppey is separated from the mainland by the Swale Estuary. This is considered to be a modified river valley at its eastern end (Allen 2000). It is here that weakening longshore drift loses the ability to transport shingle, but carries shell debris into the estuary. This creates beautiful recurved shell spits on the northern and southern shores (Fig. 17). Finally, farther west, we enter a complex of salt marsh and tidal channels in the Lower Medway and Thames estuaries, where we end our journey.

Figure 16 Cliffs at Pegwell Bay: a marine sequence of fine, silty sand (Thanet Formation and overlying Upnor Formation), a pebble bed (Harwich Formation) and clean-washed sands (Harwich Formation), topped by the basal beds of the London Clay.

Figure 17 The Isle of Sheppey and the Swale Estuary, where shingle transport carries shell debris into the estuary and creates beautiful recurved shell spits on the northern and southern shore.

References

Allen, P. 1975 'Wealden of the Weald: a new model'. *Proc Geol Assoc* **86**, 389–437

Allen, T. 2000 'The origins of the Swale: an archaeological interpretation'. *Archaeol Cantiana* **120**, 169–86

Eddison, J. 2000 *Romney Marsh; Survival on a Frontier*. Stroud: Tempus Publishing

Hadland, P. 2012 'Dinosaur footprints from the Lower Greensand *Mammilatum* bed of Folkestone?' *OUGS Journal* **33**, 63–6

Hutchinson, J. N., Poole, C., Lambert, N., and Bromhead, E. N. 1985 'Combined archaeological and geotechnical investigations of the Roman fort at Lympne, Kent'. *Britainnia* **16**, 209–36

Mortimore, R. N. 1997 'The Chalk of Sussex and Kent'. *Geol Assoc Guide* **57**, 110–17

Long, A. J., Waller, M. P. Plater, A. J. 2007 'The Late Holocene evolution of the Romney Marsh/Dungeness Foreland depositional complex', *in* Long, A. J., and Waller, M. P. *Dungeness and Romney Marsh: Barrier Dynamics and Marshland Evolution*. Oxford: Oxbow Books, 189–214

Shephard-Thorn, E. R. 1988 *Geology of the Country around Ramsgate and Dover*. BGS Memoir; London: HMSO

Ward, D. J. 1978 *The Lower London Tertiary (Palaeocene) Succession of Herne Bay, Kent*. Rep Inst Geol Sci **78/10**

Worssam, B. C., and Tatton-Brown, T. 1993 'Kentish Rag and other Kent building stones'. *Archaeol Cantiana* **112**, 93–125

Tsunamis — learning from recent events

Prof. Dave Tappin

(Principal Research Scientist, BGS, Keyworth, Nottingham)

Abstract

Tsunamis are generated by earthquakes, by volcanic eruptions and collapses, by submarine and subaerial landslides, and by meteorological disturbances. During the past 20 years there have been a number of disastrous events, mainly from earthquakes, that have resulted in the deaths of more than 250,000 people: 220,000 people perished in the Indian Ocean tsunami of 2004, and in 2011 almost 20,000 people died in Japan. A less well-known event in Papua New Guinea in 1998 killed 2,200 people; this tsunami was unusual in that it was generated by a submarine landslide and was seminal in raising awareness of the tsunami hazard from this mechanism. All these events have led to a better understanding of the hazard from tsunamis and its mitigation, but none has been predicted, flagging the fact that future research needs to better understand the hazard from tsunamis in a 'whole earth' context, relating different (mainly internal) earth processes to improve our understanding of their fundamental relationships in tsunami generation. Prof. Tappin's talk presented a synopsis on the major mechanisms of tsunami generation and tsunami impact that provides a background on how recent, often catastrophic, events have contributed to our improved understanding of how tsunamis are caused, and resulted in improved strategies of mitigation.

Background

Tsunamis have been known about from early historic times, with the first western recognition made by Thucydides in 420 BC, when an oceanic disturbance associated with a felt earthquake caused him to determine that the cause of the disturbance was the earthquake. Of course, not having any contact with Japan left him without a term for the event, the word 'tsunami' came much later from Japan, where the term means 'harbour wave'; but it was the first time that a logical conceptual explanation for the water movement had been made. We now know that tsunamis are created by vertical displacement of the seabed that travels up through the water column and creates a similar vertical movement at the sea surface, that collapses and the series of waves formed travel outwards at enormous velocities (Fig. 1). Tsunami waves in the deep ocean are hardly noticeable and not dangerous, but when the waves approach the coast, as the water shallows, their velocity decreases (from increased bottom friction) and the distance between the waves (that may be hundreds of miles) decreases. As this distance is reduced, the wave height increases (from conservation of energy) and eventually, on striking the shore, these may be tens of metres high. In fact, the highest elevation waves from an event in 1958 at Lituya Bay in Alaska, are known to have been 500m high (Fig. 2). Earthquakes, usually along convergent margins, are the most common cause of tsunamis, but recent events have shown that other mechanisms, such as submarine landslides and volcanic eruptions and collapse, can also be extremely dangerous.

Recent events

Over the past 30–40 years our understanding of tsunamis has advanced in stepwise fashion, with each new event providing an opportunity to better understand the fundamental processes governing tsunami generation, propagation and coastal run-up. This advance has been based on rapidly improving technology for recording earthquake behaviour and on computational methods to simulate and estimate earthquake parameters; also by major advances in how the seabed is mapped, such as by multibeam

Figure 1 (below) Tsunami earthquake generation mechanism (image courtesy of the University of Washington).*

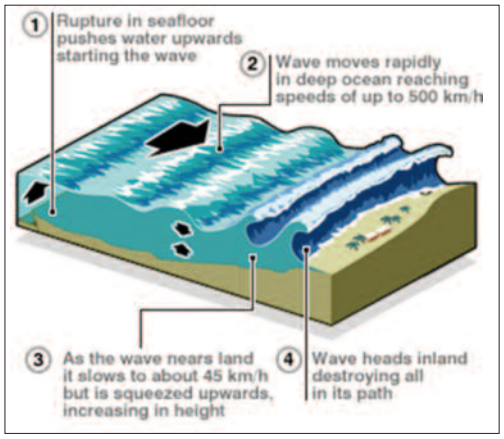

1 Rupture in seafloor pushes water upwards starting the wave
2 Wave moves rapidly in deep ocean reaching speeds of up to 500 km/h
3 As the wave nears land it slows to about 45 km/h but is squeezed upwards, increasing in height
4 Wave heads inland destroying all in its path

Figure 2 (right) Lituya Bay tsunami 1958: coastal vegetation stripped by tsunami (USGS aerial photograph of Lituya Bay taken after the July 9, 1958 event).

© OUGS ISSN 2058-5209

* *Unfortunately, some of the image files for Prof. Tappin's article are of low resolution. We have had to push them beyond the usual minimum limits for resolution — Ed.*

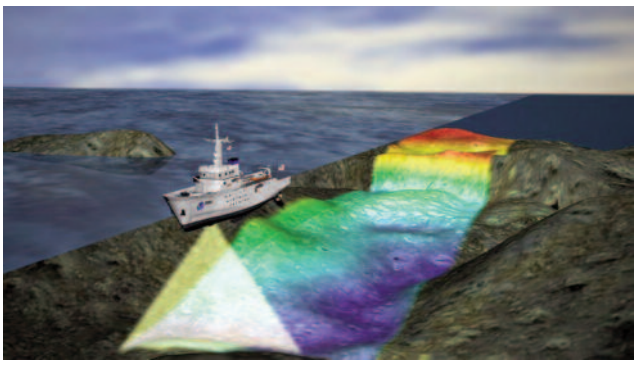


Figure 3 Visualisation of how multibeam bathymetry is acquired (source: USA National Ocean and Atmospheric Administration).

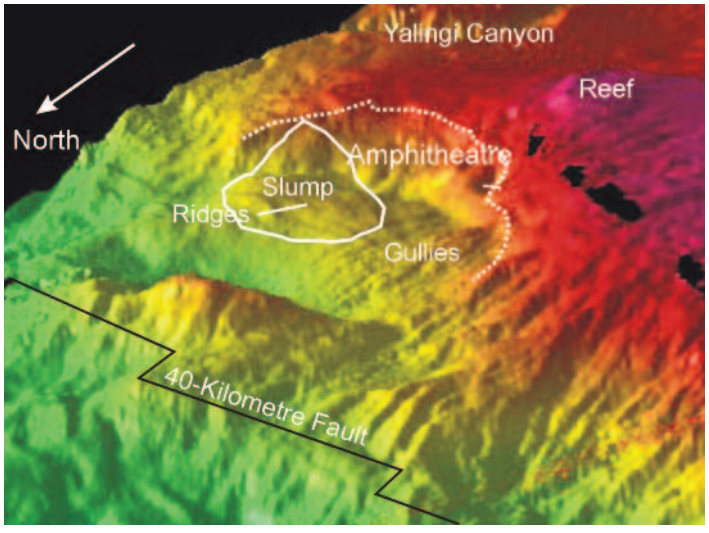
bathymetry (MBES) (Fig. 3), with the addition of greatly improved tsunami-modelling capabilities. This has led to the recognition of other important tsunami-generating mechanisms, such as submarine landslides, and volcanic collapse and eruption, and resulted in other scientific disciplines also becoming more involved in tsunami research. Before the 1990s tsunamis were mainly studied by seismologists, but now geologists are also making major contributions.

The complexity of tsunami mechanisms

The first recognition of complexity in the earthquake-generated tsunamis was in 1972 when Hiroo Kanamori realised that the scale of a tsunami is not always proportional to the earthquake magnitude (unlike the Indian Ocean event of 2004). This interpretation was based on the tsunami events of Sanriku in 1896 and in the Aleutian Islands in 1946, when Kanimori found that they were anomalous, as the scale of their associated tsunamis was far larger than would normally be predicted from their causative earthquake magnitudes. This research led to the new term 'tsunami earthquake' to identify these events.

Then in 1998, the northern coast of Papua New Guinea (PNG) was devastated by a localised, highly focused tsunami that killed 2,200 people. Again the tsunami was large in relation to the earthquake, but analysis revealed that this was not an event similar to those of the above-mentioned Sanriku or Aleutian Islands — it was not a 'tsunami earthquake'. For the first time

Figure 4 Multibeam image of the seabed slump that generated the 1998 Papua New Guinea tsunami (from Tappin et al. *2001).*



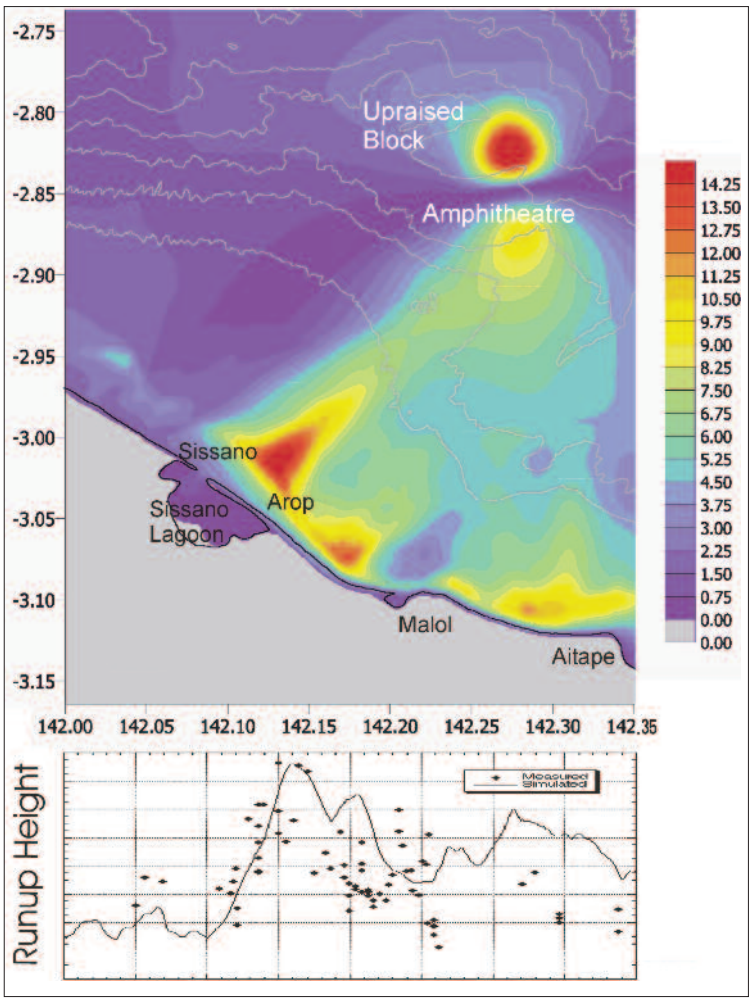


Figure 5 Time-lapse image of the maximum wave elevation (m) simulated from the slump shown in Figure 4 (top). Simulated wave maxima (solid line) agree quite well with the maximum water elevations measured by onshore surveys (diamonds) (from Tappin et al. *2001).*

responsive marine geophysical surveys were carried out that resulted in the identification of a submarine landslide just offshore of the devastated region (Fig. 4). Subsequent modelling showed this landslide to be the most likely tsunami source. Not only was this the first time that a submarine landslide was recognised as the cause of a devastating tsunami, but also new mathematical methodologies and models were developed, based on marine geophysical data, to make it possible to simulate this submarine landslide as a tsunami source; and for onshore measurements of the tsunami wave elevation to validate the results (Fig. 5).

The hazard from submarine landslides

Before PNG there was a great deal of scepticism that submarine landslides could be dangerous sources of tsunamis, but this event proved that they could be. In the wake of the PNG tsunami, a recognised need for marine surveys brought into the tsunami community a new group of marine scientists who mapped seabed structures, a traditional domain of seismologists. Advances in understanding submarine landslides tsunamis has been dependent on the recognition that, like earthquakes, one size does not fit all, and that there are numerous types of seabed failure mechanisms, ranging from slumps to translational slides, that control tsunami magnitude.

Devastation in the Indian Ocean

In 2004, the earthquake-generated tsunami in the Indian Ocean killed more than 220,000 people in nine countries and overturned accepted understanding of where 'Great Earthquakes' (larger than magnitude 9) may take place (Figs 6, 7 and 8). This event also showed that understanding of how these earthquakes ruptured was also flawed. Previously it was believed that Great Earthquakes only struck certain subduction zones, such as those off South America, Cascadia and Kamchatka, and that the main controls on these earthquakes were the rate of plate convergence and the age on the subducting crust. In 2004 this concept was 25 years out of date, with nobody considering a re-evaluation because no large events had taken place. Revision of new data accumulated since 1980, when the original research was published, revealed that the timescales over which the data was available were far too short, and that in fact the new evidence showed that most convergent margins could be subject to such large-scale events.

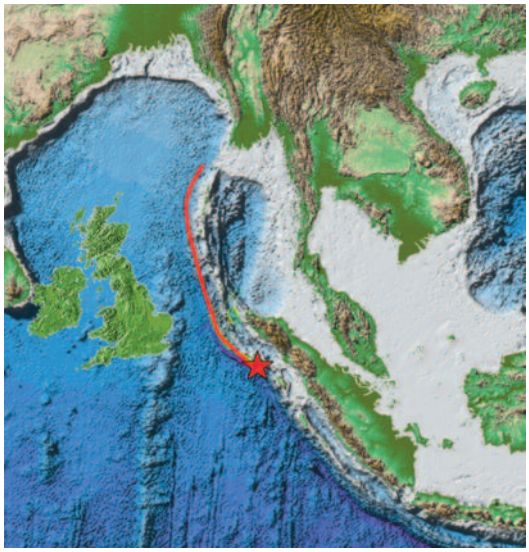
An additional important aspect of the impact of the Indian Ocean event of 2004 — as important as the new science resulting — was 'who' was involved. These natural events usually happen to 'other', often 'third world' people, but now 'we' were very much involved. For example, 550 Swedish people died in the tsunami, making it the largest natural catastrophe that country had ever experienced (Fig. 9); and 150 people from the UK also died. In the UK the tsunami was front-page news for more than six weeks as the catastrophic impact of the event unrolled. The response in the UK was enormous, as millions of Pounds poured in from individual donations; it took the UK government completely by surprise. A major cause of a significant proportion of the deaths was the lack of a warning system (only the Pacific Ocean was prepared); 120,000 people died in north Sumatra, 20 minutes tsunami travelling time away from the earthquake, but more than 100,000 people died in Thailand, Sri Lanka and India, two to three hours away from the earthquake, which would have provided plenty of time for warning and evacuation if a warning

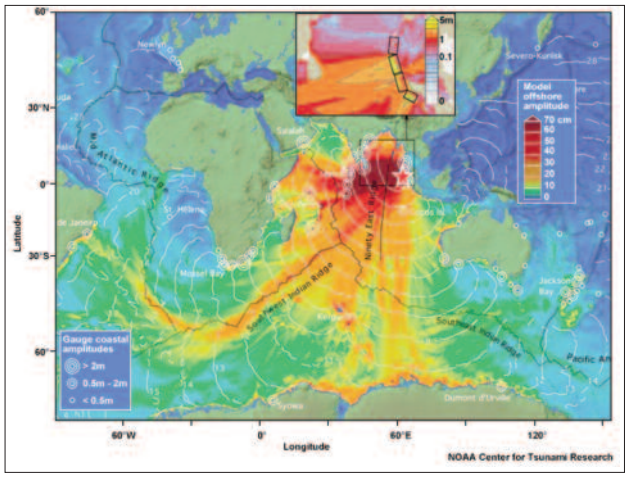
Figure 6 (below left) Earthquake rupture of 2004 Indian Ocean that generated the tsunami that killed more than 220,000 people. The star is the earthquake epicentre (UK superimposed for scale).

Figure 7 (bottom left) Global tsunami wave amplitudes of the Indian Ocean tsunami; the wave travelled around the globe three times (image from NOAA-PMEL, USA).

Figure 8 (below right) Banda Aceh, North Sumatra devastated by the 2004 tsunami (Public Domain picture taken by two sailors conducting relief operations from the USS Lincoln*).*

Figure 9 (bottom right) Swedish tourist and courageous mother, Karin Svaerd runs into the water to save her children from the tsunami in Thailand; they all survived (from Tsunami pictures).





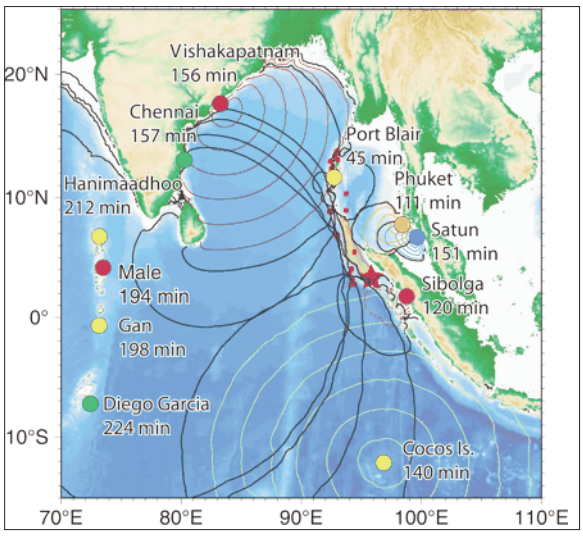


Figure 10 Indian Ocean 2004: timing of impact of tsunami wave from earthquake source on surrounding coastlines (from Lay et al. *2005).*

system had been in place (Fig. 10). Thus the event was a major 'wake-up' call on all counts, from understanding where these catastrophic events may take place through to having the systems in place to warn people and save lives. Thus one positive result of the 2004 tsunami was a massive improvement in mitigation strategies based on new models of earthquake rupture and an acceptance that devastating tsunamis can be anticipated along many convergent margins previously regarded as 'safe'.

Then Japan 2011

To everyone's amazement it was only within seven years of the Indian Ocean tsunami that another devastating tsunami struck, only this time on a well-prepared 'first world' country — Japan. The March 11, 2011 Tohoku tsunami was another devastating event; and fortunately mitigation strategies were in place, but still almost 20,000 people died. Again, although with improved understanding from the Indian Ocean and PNG tsunamis, it seems as if the 2011 Japanese event will lead to further improvement in our understanding of tsunami hazard. For Japan 2011, it now seems as if even though the earthquake magnitude was large at Mw 9, this did not generate all of the tsunami; the 40m waves (Fig. 11) that struck the north coast of Honshu island were generated by an additional source, and at present the most likely is a large submarine landslide directly offshore of the massive 40m wave elevations (Fig. 12). Again, as with the PNG tsunami, new technology such as the GPS buoys off the Japanese coast, provided a new data set that enabled discrimination between the different tsunami-generating mechanisms: earthquake and submarine landslide. But, as importantly, these buoys enabled the modelling results to be validated. Kanimori recognised 40 years ago that along some accretionary margins near plate subduction

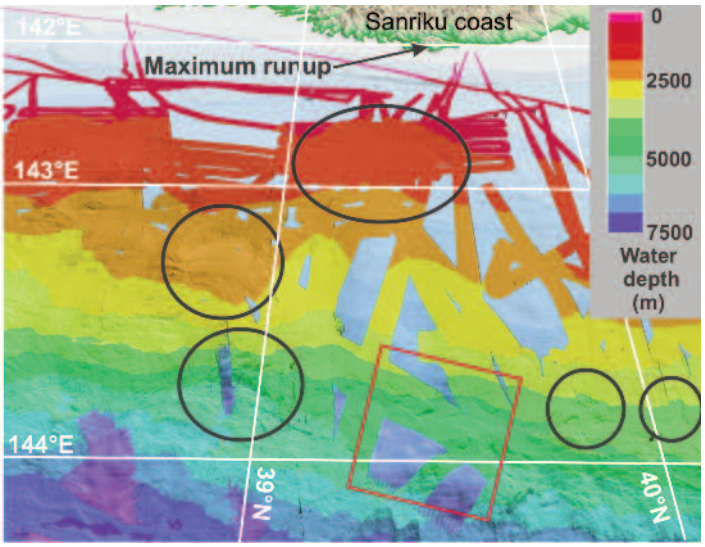
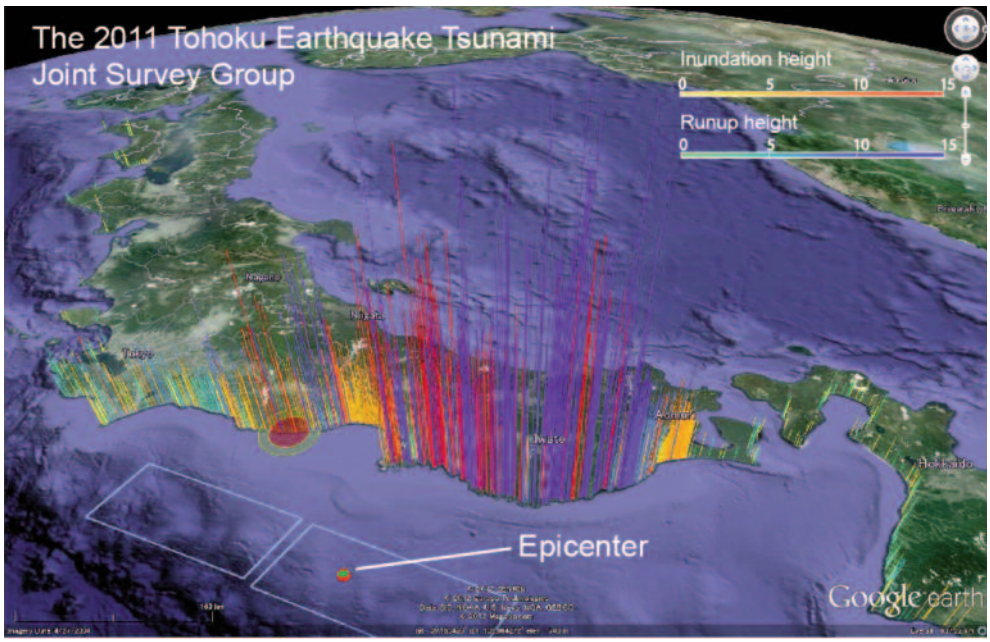


Figure 12 Submarine landslides in the region off northern Honshu (Tohoku) coast (offshore Iwate located in Fig. 11) from pre-March 2011 JAMSTEC bathymetry: black ellipses = locations of landslides; red square = the location of the landslide triggered by the March 2011 earthquake (from Tappin et al. *2014 — Open Access).*

Figure 11 Japan 2011: Tsunami elevations at the coast (run-up) and inland (Inundation). Note the highest elevations around Iwate compared to the location of the epicentre (farther south) (image from the 2011 Tohoku Earthquake Tsunami Joint Survey Group).



zones, thick sediment accumulations along the toe of the accretionary prism can produce a 'damping' of seismic energy, resulting in the 'tsunami earthquakes'. Therefore we now know from the 2011 Japanese event that a large earthquake can trigger large-volume submarine landslides, which can cause local high-elevation waves. Thus along some subduction margins, (e.g. northern Japan) an earthquake may trigger a massive submarine landslide that sources an additional, highly focused tsunami with elevated run-ups, such as were experienced along the northern Honshu coast in 2011. Recognition of this is leading to a re-evaluation of older events such as those that took place in Alaska in 1946 and in Java in 2006 to determine whether these too were not just earthquake-generated.

The future is bright

In many respects the new research on the Japanese event squares the circle of relating earthquake and submarine-landslide-generated tsunamis first recognised in the PNG event. It is increasingly apparent that there may well be a continuum between earthquake and submarine landslide tsunamis, with these two mechanisms as end members. If correct, and the new evidence is formidable, a critical lesson learned for future tsunami hazard assessment along subduction zones worldwide is that, although tsunami hazard assessment requires simulating massive M9 earthquakes, the greatest (and most hazardous) run-ups may be due to local secondary processes, such as submarine landslides. This hazard may well be overlooked in the context of a great M9 earthquake, but from the 2011 Japanese event we know that a tsunami generated from the landslide could be far more destructive. Therefore, this possibility has to be considered to formulate effective mitigation. As noted above, in the broader context, the new research has important implications for understanding other anomalous — and controversial — events, such as the disasters in Alaska in 1946, Flores Island in 1992 and Java in 2006.

Where we need to go

A critical aspect of the new tsunami research is its multi-disciplinary nature; relying on collaboration between seismologists, marine geologists, engineers and tsunami modellers. Our new understandings address major problems important to society: the better understanding and mitigation of geohazards caused by tsunamis. The past 20 years have seen major improvements in our understanding of the hazard from tsunamis, and, although we have come far, there are still further challenges to be faced. Global warming may increase the likelihood of seabed instability with increased likelihood of submarine-generated tsunamis. We still do not understand tsunamis caused by volcanic eruption, such as the Krakatau eruption of 1883, when more than 60,000 people died along the coasts of Java and Sumatra. The greatest potential tsunami hazard to the UK is collapse in the Canary Islands. Whereas warning from tsunamis generated from far-away sources has improved significantly since 2004, with all the world's major ocean basins now having warning systems, warning coastal communities of dangerous events from nearby sources just offshore is still difficult because of the short travel times between the tsunami source and the impact. It is also the case that all warning systems are based on earthquake sources; submarine landslides are not considered.

The most important aspect now, however, is that many coastal populations in threatened regions are better prepared than they were ten years ago when the 2004 Indian Ocean tsunami killed more than 220,000. And one major lesson learned is that even without the sophisticated warning systems in place, local people know that, if they feel an earthquake, this may be a strong warning and they should escape to high ground.

Further reading

Grilli, S. T., Ioualalen, M., Asavanant, J., Shi, F., Kirby, J., and Watts, P. 2007 'Source constraints and model simulation of the December 26, 2004 Indian Ocean tsunami'. *J Waterway Port Coastal Ocean Engineering* **133**, 414–28

Kanamori, H. 1972 'Mechanisms of tsunami earthquakes'. *Phys Earth Planet Inter* **6**, 346–59

Lay, T., Kanamori, H., Ammon, C. J., Nettles, M., Ward, S. N., Aster, R. C., Beck, S. L., Bilek, S. L., Brudzinski, M. R., Butler, R., DeShon, H. R., Ekstrom, G., Satake, K., and Sipkin, S. 2005 'The great Sumatra-Andaman earthquake of 26 December 2004'. *Science* **308**, 1127–33

McCaffrey, R. 2008 'Global frequency of magnitude 9 earthquakes'. *Geology* **36**, 163–266

Satake, K., and Tanioka, Y. 1999 'Sources of tsunami and tsunamigenic earthquakes in subduction zones'. *Pure Applied Geophys* **154**, 467–83

Stein, S., and Okal, E. A. 2007 'Ultralong period seismic study of the December 2004 Indian Ocean earthquake and implications for regional tectonics and the subduction process'. *Bull Seismol Soc Amer* **97**, S279–95

Tappin, D. R. 2010 'Digital elevation models in the marine domain: investigating the offshore tsunami hazard from submarine landslides', *in* Fleming, C., Marsh, S. H., and Giles, J. R. A. (eds), *Elevation Models for Geoscience*. London: Geol Soc Special Publ, 81–101

Tappin, D. R., Sibley, A., Horsburgh, K., Daubord, C., Cox, D., and Long, D. 2013 'The English Channel 'tsunami' of 27 June 2011 — a probable meteorological source'. *Weather* **68.6**, 144–52

Tappin, D. R., Grilli, S. T., Harris, J. C., Geller, R. J., Masterlark, T., Kirby, J. T., Shi, F., Ma, G., Thingbaijam, K. K. S., and Mai, P. M. 2014 'Did a submarine landslide contribute to the 2011 Tohoku tsunami?' *Marine Geol* **357**, 344–61

Tappin, D. R., Watts, P., McMurtry, G. M., Lafoy, Y., and Matsumoto, T. 2001 'The Sissano, Papua New Guinea tsunami of July 1998 — offshore evidence on the source mechanism'. *Marine Geol* **175**, 1–23

Tappin, D. R., Watts, P., and Grilli, S. T. 2008 'The Papua New Guinea tsunami of 17 July 1998: anatomy of a catastrophic event'. *Nat Hazards Earth Syst Sci* **8**, 243–66

Book review

Park, Graham 2014 *The Making of Europe: a Geological History*. Edinburgh: Dunedin Academic Press (ISBN 978-1-78046-023-9; paperback, 164pp; £24.99)

This book is a comprehensive overview of how the shape and structure of Europe as we know it today came about. It describes the tectonic evolution and geological events that contributed to its formation from the Precambrian to the Cenozoic.

After a short, basic introduction, the book begins in the Pre-Cambrian by describing the stable core of a Proto-Europe, the East European Craton and the various domains, provinces and suture zones that contributed to its make-up. The addition of other elements to this core is described in the context of the global plate tectonic movements during the Paleozoic. There is a chapter on the Caledonian Orogeny, and another on the Variscan and Uralian orogenies. Moving on to the Mesozoic, Europe's relationship to Pangaea and its breakup is described, followed by a chapter on the Alpine Orogeny, by which time Europe had roughly reached its present shape. The book finishes with a chapter on the most recent changes that affected the history of the growth of Europe during the late Cenozoic.

Professor Park describes the tectonic movement of the various landmasses about the globe coming together, colliding and drifting apart as if they were flotsam and jetsam on a lazy tide.

The book is copiously illustrated with colourful figures, which repay careful study in conjunction with reading the text. The current outline of Europe has been superimposed on the illustrative maps of the zones, terranes, provinces, shields, seas, etc. that made up the geology of Europe at different time periods, so that some idea can be gained of their relationship to the present. Cartoons of the tectonic evolution through time, showing the opening and closing of oceans, terrane assemblage, formation of mountain belts, and of fault zones, etc. are very informative. Photographs illustrating various aspects of the geology are also included, with annotated satellite images of geological tectonic features being particularly interesting. A glossary is provided of some technical terms and geological names, but is not wholly comprehensive. There is also a short list of selected further reading, but not a complete bibliography.

I'm not quite sure who the book is aimed at. The preface states "the reader is assumed to have an understanding of basic geological terms and concepts", but I asked a friend, who has a basic knowledge of geology, to read some of it and he found it very difficult. I also found it challenging at times, but an interesting read.

— Suzanne Grain MSc (Open), BSc Hons (Open), BA Hons (Wales)

Quaternary evolution of the North Sea and the English Channel

Prof. P. L. Gibbard

(University of Cambridge, Cambridge Quaternary, Department of Geography)

Dr K. M. Cohen

(Utrecht University, Rhine-Meuse Delta Studies, Department of Physical Geography)

Abstract

The island of Britain is surrounded by a 'moat' of water, of which the English Channel and the North Sea are two major components. This talk described some major events that occurred to shape these seaways and, in particular, the evidence preserved on the Channel seabed. Here a system of valleys occurs that was carved by the westward-flowing Channel River. At its maximum in the last glacial period this river was larger than any other river in Europe today. It carried water not only from the rivers currently entering the Channel, but also from rivers flowing into the southern North Sea. Today the Holocene is characterised by limited glaciation and therefore high sea level. However, for much of the time, global sea level was lower, exposing shallow areas as dry land.

Throughout the last 2–3Ma, the build-up and decay of ice sheets on the continents have driven spectacular changes of global sea level. Driven by climatic fluctuations, these sea-level changes resulted in cycles of emergence and submergence of the Channel floor. About 500,000 years ago the English Channel and the North Sea were flooded, as they are today, but unlike today there was a substantial land barrier, the Weald–Artois ridge, that linked Britain to the European continent. During cold periods up to 500,000 years ago the two seas were drained by separate river systems: the Channel River, aligned along the Channel basin's axis, drained towards the Atlantic Ocean, while in the North Sea the major rivers flowed northward.

Although there were earlier events, the first major extension of a continental-scale ice sheet into lowland central Europe and Britain occurred c. *450,000 years ago (the Anglian advance). Critically, this ice advanced across the emergent North Sea floor from the mountains of southern Scandinavia and Scotland, blocking the northward-flowing rivers and causing an immense glacial lake to develop in the basin south of the ice front. Once dammed, the water that continued flowing from most of western Europe's rivers caused the lake level to rise. The substantial land barrier of the Weald–Artois anticline held up the water and it was this barrier that was overtopped and breached. The narrow waterway thus formed became the Dover Strait (a.k.a. Pas de Calais), linking the North Sea to the English Channel.*

The breaching of the ridge to form the Dover Strait was critical to the evolution of the Channel from then onward, up to the present. It forced the rivers Thames and Scheldt to flow through the new Dover Strait and into the Channel River. This drainage system continued to evolve for the next 200,000 years, but events were brought to a climax some 160,000 years ago when a second major continental-scale glaciation occurred (known as the Saalian advance). The resulting megafloods sealed Britain's fate: during high sea-level periods it would henceforth be an island.

The implications of such striking geographical changes for plant and animal — including human — migration are profound, resulting, among other things, in the impoverishment of British flora and fauna during warm periods such as today's British climate, but providing a major route between the Continent and Britain during glacial periods. In addition, the rapid release of huge volumes of fresh water in megafloods into the Atlantic Ocean could have triggered changes in oceanic circulation, which, in turn, could have affected the climate of the whole North Atlantic region.

[OUGS Canterbury Symposium: Marine Geotales; original transcription by Dick Millard from the seminar recording; written up by Prof. Gibbard and Dr Cohen]

Introduction

The Quaternary evolution of the North Sea and the English Channel is a history of change of drainage systems, and the interaction of these drainage systems with glaciation, sea level, and climate change and tectonics. For Britain, the development of a sea that separates our island from the Continent is central to the evolution, as it includes not only the formation of the Strait of Dover, but also the evolution of the North Sea and the English Channel. The drainage system history begins in the Neogene. The process of connection of North Sea and English Channel commenced in the Middle Pleistocene. The OUGS lecture and this article summarising that lecture, spans the full development. Key references are provided in the captions of the selected figures.

The Quaternary Period in which we live today spans 2.6 million years and includes very high-frequency change, indeed the main characteristic of this period is climate change. During the Last Glacial Maximum (or LGM) ice sheets in the Northern Hemisphere extended across the continents into what are today temperate regions. The ice sheets, like the Fennoscandian ice sheet, the small ice sheets on the British Isles, the large Laurentide ice sheet on North America (the largest ice sheet on Earth) were present at maximum extent *c.* 20,000 years ago only and receded up to *c*. 8,000 years ago. In Britain, the ice extended as far south as the English Midlands and the northern coast of Norfolk. In fact, we are still living in an ice age, you might think, for even today there is ice over Greenland, indicating that we are still very much in 'the' Ice Age; and, of course, we humans are products of that Ice Age.

It is well established that during glacials, the accumulation of ice on the land caused lowering of the global ocean. During the Last Glacial Maximum, for example, the global ocean level stood at 120m below present level. This caused the continental shelves around Britain in particular — but around the rest of the continents as well — to be mostly exposed, and therefore Britain was not an island as little as *c.* 9,000 years ago, well into the Early Holocene (the current interglacial). With the melting of ice on

© OUGS ISSN 2058-5209

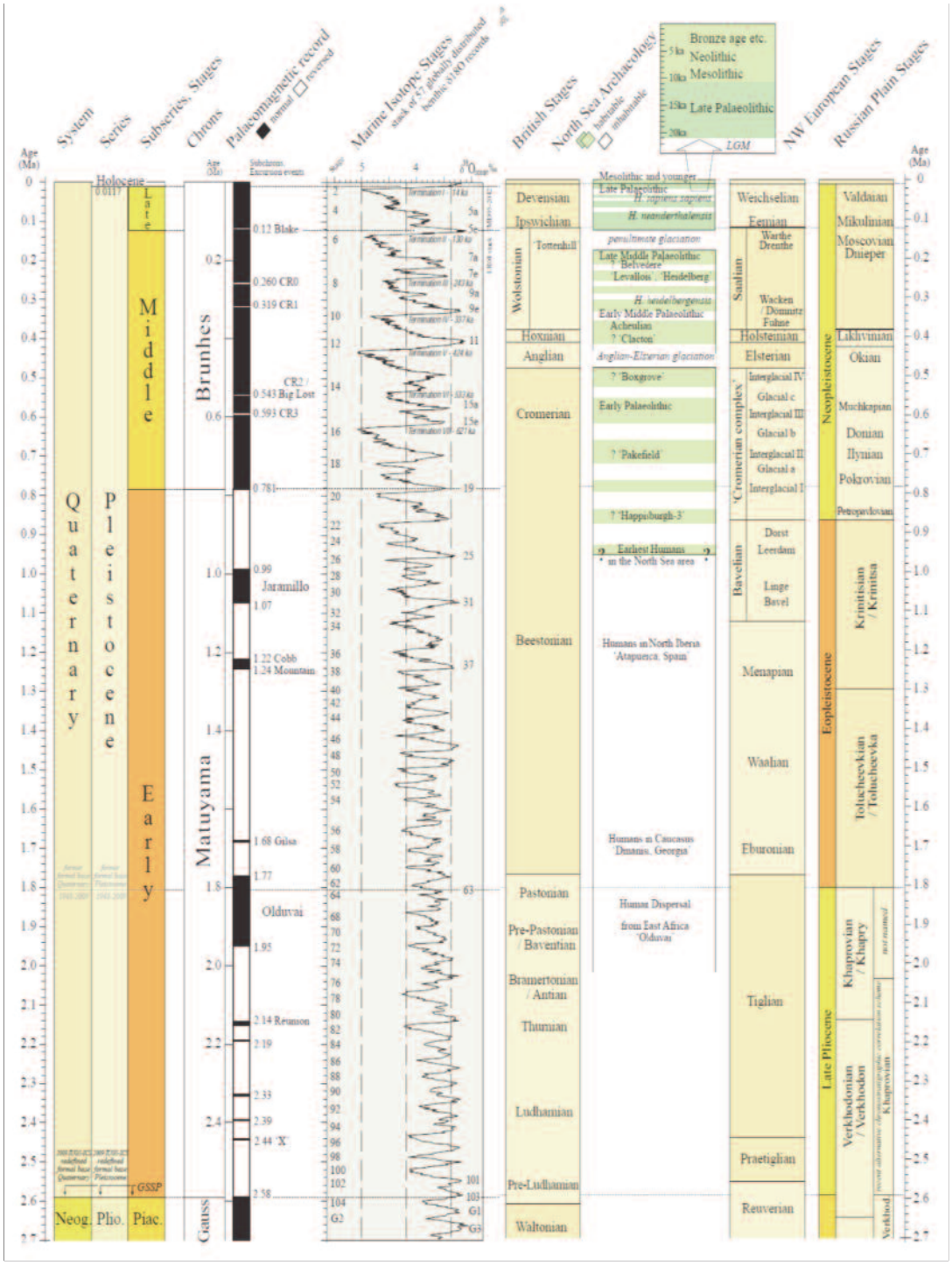


Figure 1 Chronostratigraphical correlation chart for the Quaternary, showing global divisions (IUGS International Commision on Stratigraphy), marine oxygen isotope stages from the marine record (Lisiecki and Raymo 2005), and further division schemes, including that of the regional British Stages (based on Gibbard and Cohen 2008; ICS Subcommission on Quaternary Stratigraphy).

land, at the end of every glacial and well into the interglacial, the sea level rises to a level as we see today. Indeed, sea-level change is a critical point in understanding the development of the North Sea and English Channel and will recur in our discussion of their drainage evolution. Associated with the sea-level climate change are massive biotal changes. This involved the migration of the whole biota — plants and animals — being driven by repeating glacial-interglacial cycles (Fig. 1).

The latest plot of the division of time during the Quaternary shows that there are a number of different ways in which we can define the period. Herein the marine isotope curve from deep-sea sediment cores is critically important. It is based on measurement of the $^{18}O/^{16}O$ oxygen isotope ratio recorded in Foraminifera (value expressed as ‰ deviation to a modern seawater standard). Those data show each prolonged climate oscillation within the last 2.6 million years of the Quaternary as a continuous and well globally averaged signal. The scale of these oscillations can be seen to have increased as we approach the present day. Notably for the youngest 800,000 years, a marked increase in the intensity of climate oscillation is indicated. The time interval over which this change occurs has been termed the Middle Pleistocene transition (*c.* 1.2–0.8Ma). So, especially in the youngest part of the Pleistocene, several major northern hemisphere glaciations are evident, each separated by interglacials, or temperate periods. In these last 800,000 years, each glacial cycle shows a saw-tooth pattern, in which glacial maxima recurred every 100,000 years.

Over northern Britain and Scandinavia, ice sheets developed during these glacial half cycles. The timing and magnitude of the maximum extent of the 'glaciations' of Britain, Scandinavia and the surrounding shelves matches broadly (but does not correlate precisely) to the glacial maxima in the marine isotope record. Interspersed between those glaciations were interglacials comparable to the Holocene. By 'comparable' we mean with climate, sea level, vegetation cover and animal communities similar to those found today. Obviously there has been change through that period and physical changes of the landscape and of biota have occurred in concert. Landscape evolution and biological evolution together have led to differences between the flora and fauna of older and younger glacials and interglacials, which helps us to recognise and attribute sediments from subsequent glacial and interglacial periods.

Here we present a palaeogeographical overview of the last three million years, and this includes the periods before, during and after the formation of the Dover Strait. We feel the formation

of the Dover Strait is a very critical change for Britain because clearly it had enormous implications, not just in terms of our separation from the Continent but also because it provides a boundary that plants and animals cannot cross — and that includes humans, especially when the ferries aren't running — so that is a turning point in the history of this region. Following from that, we discuss the tectonic and geomorphological setting (if you like, the dynamic tectonic-geomorphological interaction), sedimentary and palaeoenvironmental records and the reconstructed landscapes and processes that operated during this period.

The Late Pliocene to Early Pleistocene, 3 to 1 million years ago: the initial drainage pattern

We begin by discussing a map showing tectonic structural elements in Western Europe, summarising a reconstruction by Ziegler (1978). It shows three major tectonic components to have affected the distribution of land and sea, the drainage and also the glaciations in our study area. This inherited geological setting underlies the whole of the further story.

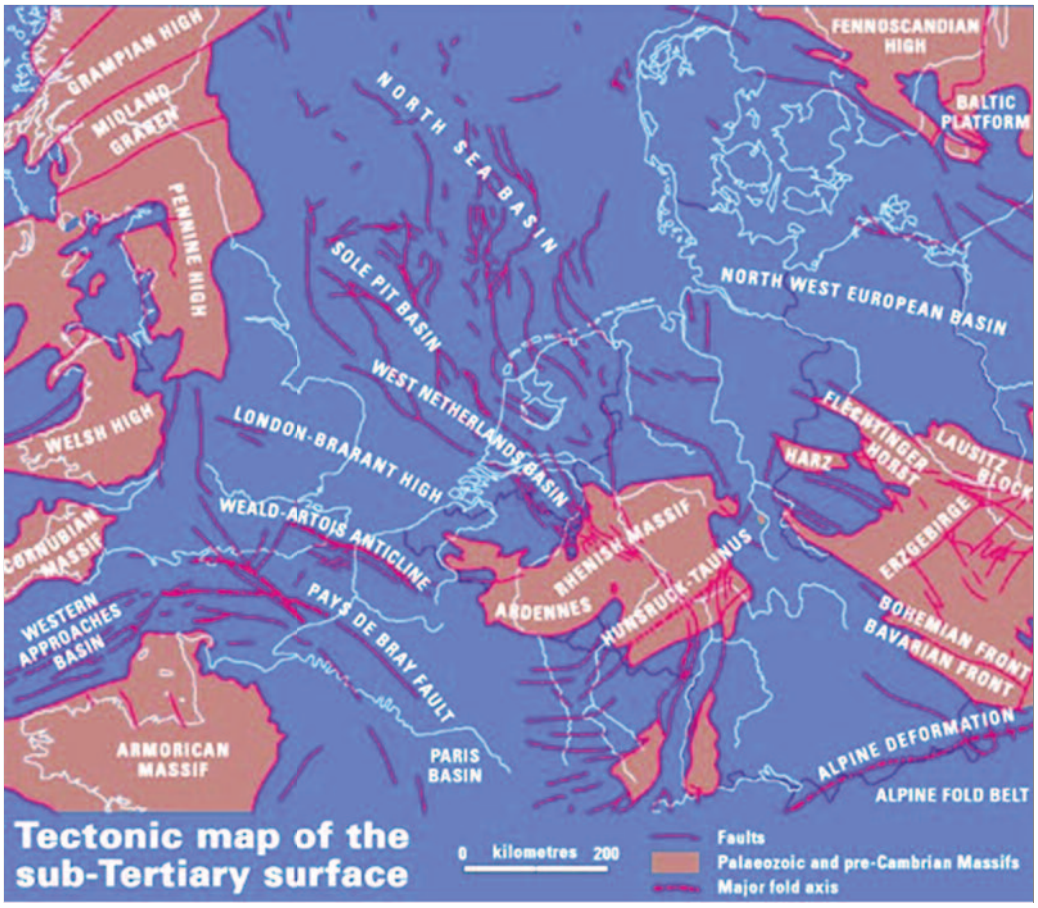
Figure 2, in orange, shows a series of massifs or crystalline blocks along the western side of the Eurasian continent (e.g. Welsh High), continuing into France (Armorican Massif). These crystalline basement areas represent uplifted blocks. There is also the important Fennoscandian High underlying Scandinavia; and similar structures forming the Rhenish Massif, the Ardennes and the Hunsrück, etc., and then to the northern Alps. These rigid blocks are mostly composed of Palaeozoic rocks. Younger geological areas between these blocks show very strong tectonic alignments. The most obvious is that aligned down the central North Sea, through the Netherlands, through the Rhenish Massif and then down the Rhine rift valley towards the Alps. This is a failed continental suture along which in a much earlier past (in the Mesozoic, when the Atlantic Ocean was opening) the continent could have rifted apart (but did not). It is still an active tectonic area: in 1992 a magnitude 5.8 earthquake occurred in the south-east Netherlands along a main fault in this suture. A parallel structure is a very large transform fault (the Fécamp Fault), which runs through the Paris Basin, continues into the Isle of Wight as the monocline and around into the Western Approaches Basin area. This gives a north-east/south-west alignment, which is associated with the opening of the Atlantic Ocean, causing uplift along the western margin. At right angles to this, are the Alpine deformation structures associated with the orogenesis of the Alps — the closing of the Mediterranean and the movement of Africa towards the European continent. This has given us a whole series of structures in a broadly east–west orientation, including the North West European Basin, which runs through Denmark, north Germany and into Poland. A particular one to note is the Weald–Artois anticline, because it links the British Isles with the Paris Basin structure and, with the London-Brabant High, underlies the zone of land that linked the British Isles area with the Continent throughout much of the Pleistocene.

Figure 3 (*overleaf*) shows the palaeogeography of three million years ago. It was originally drawn in 1988 and there are minor changes since, but the critical feature to note is that the North Sea and English Channel are not linked. They are separated by a major continental-scale 'interfluve' upland area. North of the interfluve, there is the London Basin area, drained by the Thames, which had headlands in North Wales at this time.

The structurally controlled, sub-parallel alignment of the drainage systems is noteworthy. This is because of the upland topography that during the Neogene had developed in response to uplift on the western side of Britain, in contrast to the lowland and shelf sea situation in the subsiding North Sea Basin. The latter area was a major ocean-connected shelf-sea embayment where shallow marine and deltaic sediments accumulated. South of the North Sea, drainage from the Weald towards the south is aligned into the Channel, including the major Solent River, originally identified by Clement Reid in the late 19th century.

On the continental side of the North Sea, a series of river systems can be seen. Minor river systems in Belgium, the Scheldt (or *Schelde*) and its associate streams, continue like those on the British side of the Weald, and the larger rivers Meuse (*Maas*) and Rhine (*Rhein*, *Rijn*) join from the south-east. Note that important Alpine-foreland headwaters of the Rhine only linked to the downstream parts of the system at *c.* 2.6Ma (before that time, the

Figure 2 Tectonic map of the sub-Tertiary surface (after Ziegler 1978; Gibbard 1988).



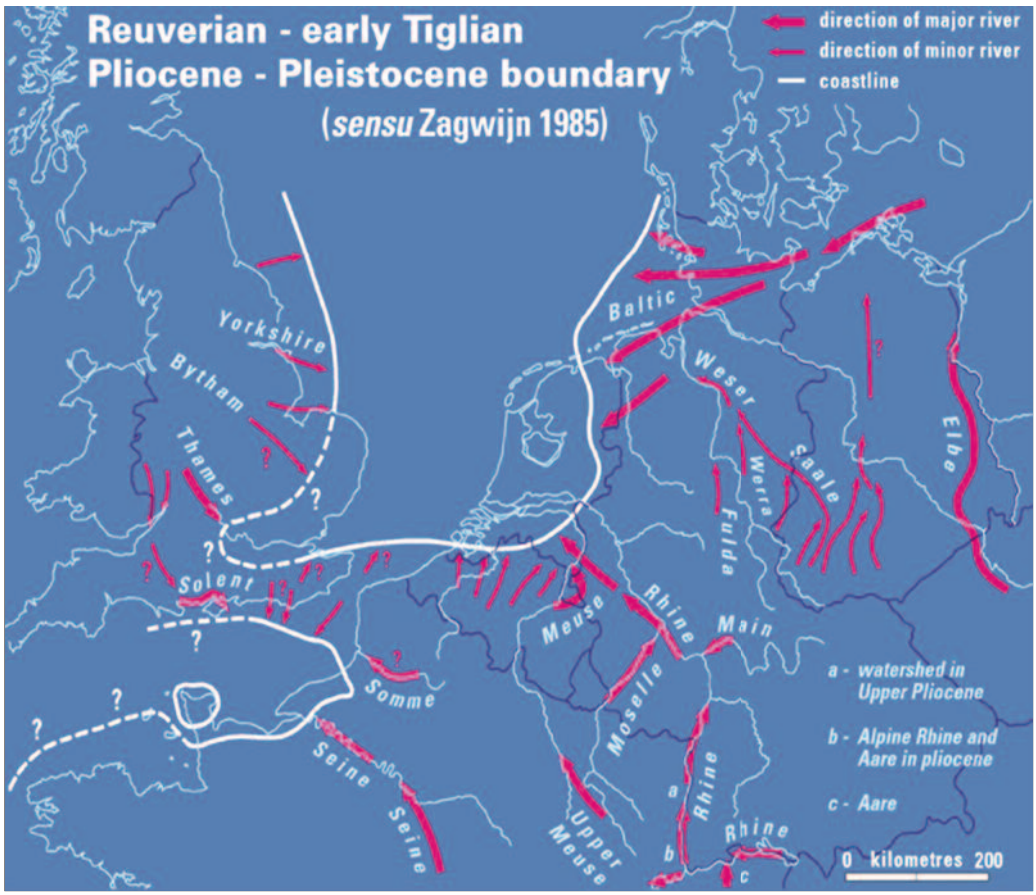


Figure 3 Drainage and palaeogeography at the beginning of the Pleistocene (after Gibbard 1988).

alpine reaches were part of the Rhône system and drained into the Mediterranean). The major drainage system at this time, much bigger than the Rhine today, was the Baltic River System, sometimes referred to as the Eridanos River. This major river ceased to exist over the course of the Pleistocene, but it had been active throughout the Neogene, building out its delta and feeding the North Sea shelf seas with sediment, filling more and more of the accommodation space and pushing the coastlines of the embayment north-westward. As tributaries, this river included precursors of the rivers Elbe (draining from Czechoslovakia) and Weser (central Germany).

In the Channel region, the Somme and the Seine were already in existence. At this time, the Seine's course included headwaters in the Massif Central. Uplift of the Massif Central, as a consequence of Alpine earth movements, caused the headwaters of the Seine to be diverted to become the headwaters of the Loire, so the Seine was effectively beheaded by this time.

From this palaeogeographical setting, in the British sequence there are Plio/Pleistocene marine sediments in East Anglia (Fig. 4, *opposite*), the so-called crags. These extend relatively far inland and up to quite high levels. In Hertfordshire they occur up to 120m above present sea level, so there must have been uplift of the western region of Britain in the youngest 3Ma. Farther east, these deposits occur at sea level and below offshore. They underlie the North Sea and the same type of system occurs on the Flemish-Dutch side within the Westkapelle Ground and Maassluis Formations (offshore and onshore, respectively). As shown by the section across the North Sea from East Anglia to near IJmuiden in the Netherlands, a substantial sedimentary wedge underlies the North Sea, reaching more than 600m thickness underneath the coastal Netherlands (Fig. 4). On the British side, the Crag Group sediments are very thin by comparison. This distribution reflects the differences in subsidence regime between the English and Belgian sectors of the Southern Bight, and the Dutch sector of the North Sea (echoing the structural alignments in Fig. 2). The Crag deposits were laid down about 2.3 or 2.4 million years ago when the Thames Basin was occupied by the sea. As time advanced into the Early Pleistocene, there was a progressive migration of the coastline towards the north. This has been tracked by the offshore mapping using the very detailed seismic techniques now available. This progressive migration of the coastline northward is mainly a result of input of fluvial sediments by rivers around the North Sea Basin, but in particular by input of sediment from the Baltic System.

The Baltic River system (the Eridanos), would probably still exist today if major glaciations had not occurred in the Middle Pleistocene. In the Early Pleistocene, the Eridanos was draining most of Fennoscandia and draining the Baltic states and adjacent portions of Russia (Fig. 5, *opposite*). The Baltic Sea area, in the Early Pleistocene was a river system, not the marine embayment it is today. This is confirmed by the massive volumes of river-delivered sediment in the central and northern North Sea. From the Pliocene/Early Pleistocene boundary onwards, in the northern North Sea we see the presence of an ice sheet on nearby Norwegian Scandinavia, as iceberg scours in seismics and as occasional dropstones in otherwise ordinary shallow marine deposits. At the same time, the Baltic River system migrated out into the North Sea and here you see the tracks of floating icebergs from floating ice present in Norway *c.* 2.5 million years ago. They track southwards: the currents would still carry ice in that direction if we had floating ice up there today (Fig. 6, *page 68*).

Beginning of Middle Pleistocene, up to 500,000 years ago: the 'Cromerian Complex'

The second period considered here is termed the 'Cromerian Complex' Stage of the end of the Early to the early Middle Pleistocene, beginning roughly one million years ago (*see* Fig. 1; Middle Pleistocene transition) and running up to the Anglian glaciation (that began *c.* 470,000 years ago). As already mentioned, during this time period, the glacial-interglacial climate oscillations were more profound than before, and this led to the development of more substantial ice sheets in northern Europe, North America and elsewhere.

There probably were glaciations in the Alps and of north Wales and certainly in Scandinavia at this time. The first of the really extensive glaciations is the so-called Don glaciation, named after

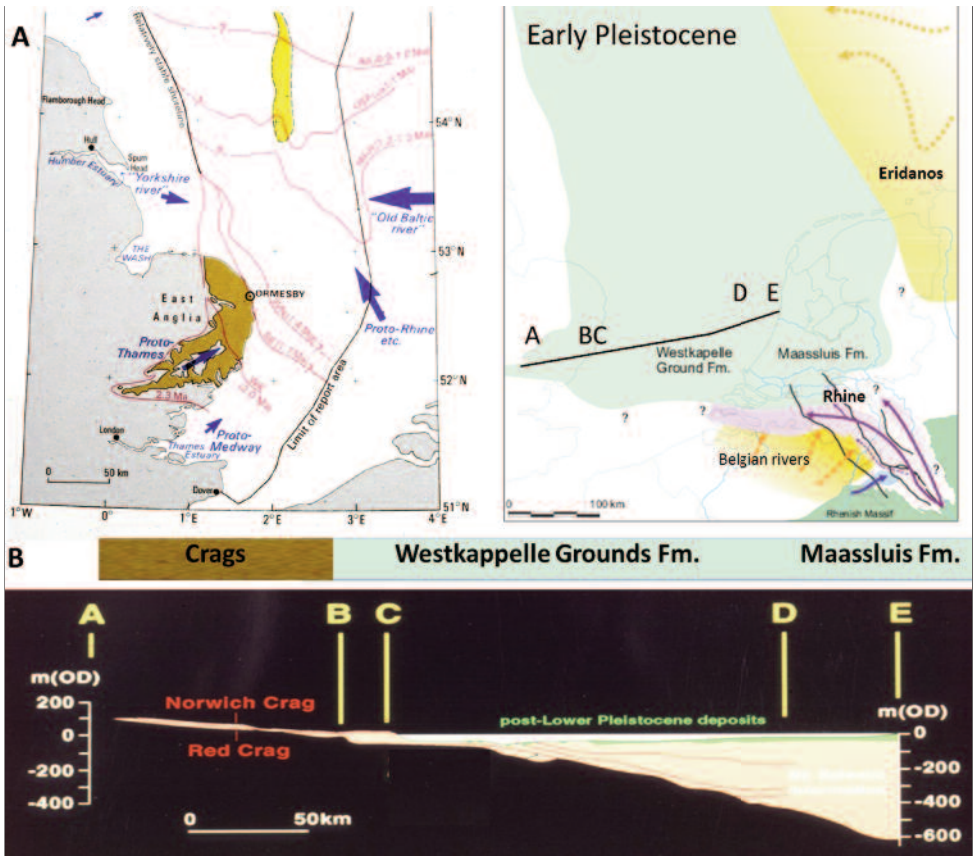


Figure 4 (A) The mapping of the Crag Group sediments and Early Pleistocene coastline migration in the British sector of the North Sea (from Cameron et al. *1992), and for the Netherlands' offshore and onshore parts of the basin (from Westerhoff 2009); (B) W–E cross-section through the Quaternary of East Anglia and the southern North Sea (teaching material © P. L. Gibbard).*

the Don Valley in Russia, about 650,000 years ago. However, before the Anglian, ice sheets did not manage to cover our region of interest. Indirectly and marginally, the Cromerian Complex glaciations did affect the study area; directly they did not yet do so. Figures 7 (*overleaf*) and 8 (*page 69*) thus show the geographical setting of the region before major glaciations occurred and affected the lowlands of the south of Britain and the south of the North Sea. They carry less detail in the Middle Pleistocene glaciated north than in the unglaciated south.

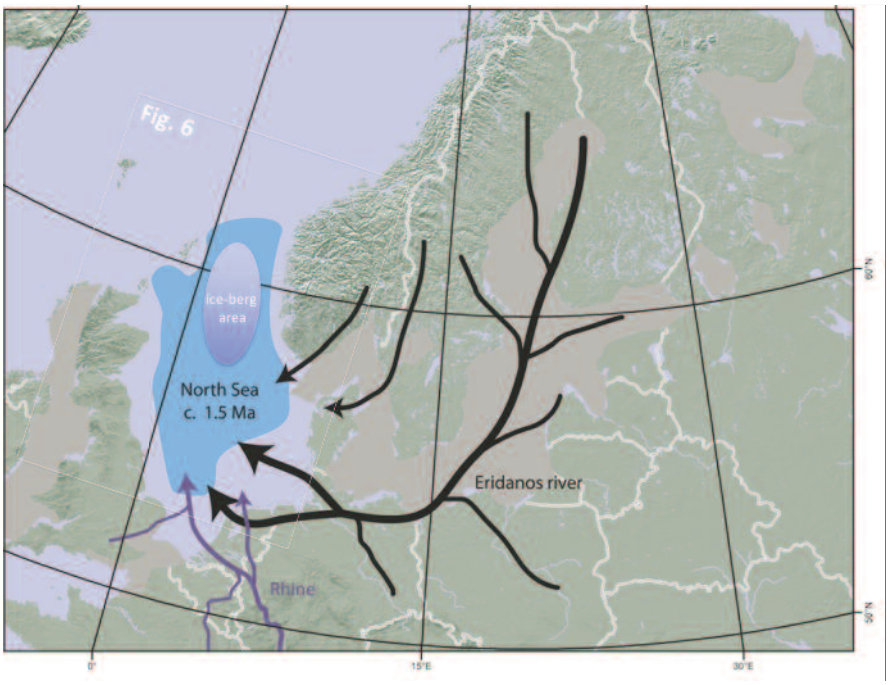
By the time of the Middle Pleistocene, the Rhine had become a significantly more important element in the southern North Sea region. The protruded Rhine deltaic complex by this time had filled the whole of the central and southern North Sea. Particularly at low sea-level stands, the southern North Sea became a major lowland area. To the south, the interfluve formed by the Weald–Artois anticlinal structure continued to be present. In the south-west, this structure of the major drainage lines still occurred, including the Thames and its tributaries from the Weald, drainage from the western side of Britain (the Midlands), possibly a Yorkshire River and rivers farther north (though these are poorly represented). On the eastern side of the North Sea, the northern (Baltic) river system by this time appears to have lost the connection to the Fennoscandian and Baltic headwaters. This implies that at this time the Baltic had been formed, as a consequence of intensified glacial erosion by the more substantial ice-sheets. Nevertheless, along this northern course within the North European Basin (*see* Fig. 2), major input occurred from Scandinavian glacial outwash, adding to the water and sediment discharge of Elbe and Weser, and in the North Sea area mixing with that of Rhine, Meuse, Scheldt and Thames.

South of the Weald–Artois interfluve the drainage systems were in the same positions as before. On the British side of the Channel, the Solent River remained a major input from the Hampshire Basin. On the southern side of the Channel, the Seine and the Somme occurred, and together with the British rivers entered the substantial Channel River system (or *Fleuve Manche*), which occurred on the floor of the basin during low sea-level stands. This Channel River would play a crucial receiving role in the drainage evolution of the region subsequently.

Ancient humans in the landscape of the 'Cromerian Complex'

At this point it is important to stress that the drainage systems and the palaeogeography described so far have been predominantly the sort that occurs during 'low-stand', or cold and glaciated periods (i.e. as shown in Fig. 7). However, intervening between the glacial, or cold-climate intervals there are also interglacial periods, like that in which we live today, which are temperate and warm (i.e. as shown in Fig. 8). Recent studies have shown the distribution of

Figure 5 Extent of the Eridanos river system in the Early Pleistocene (from Cohen et al. *2014).*



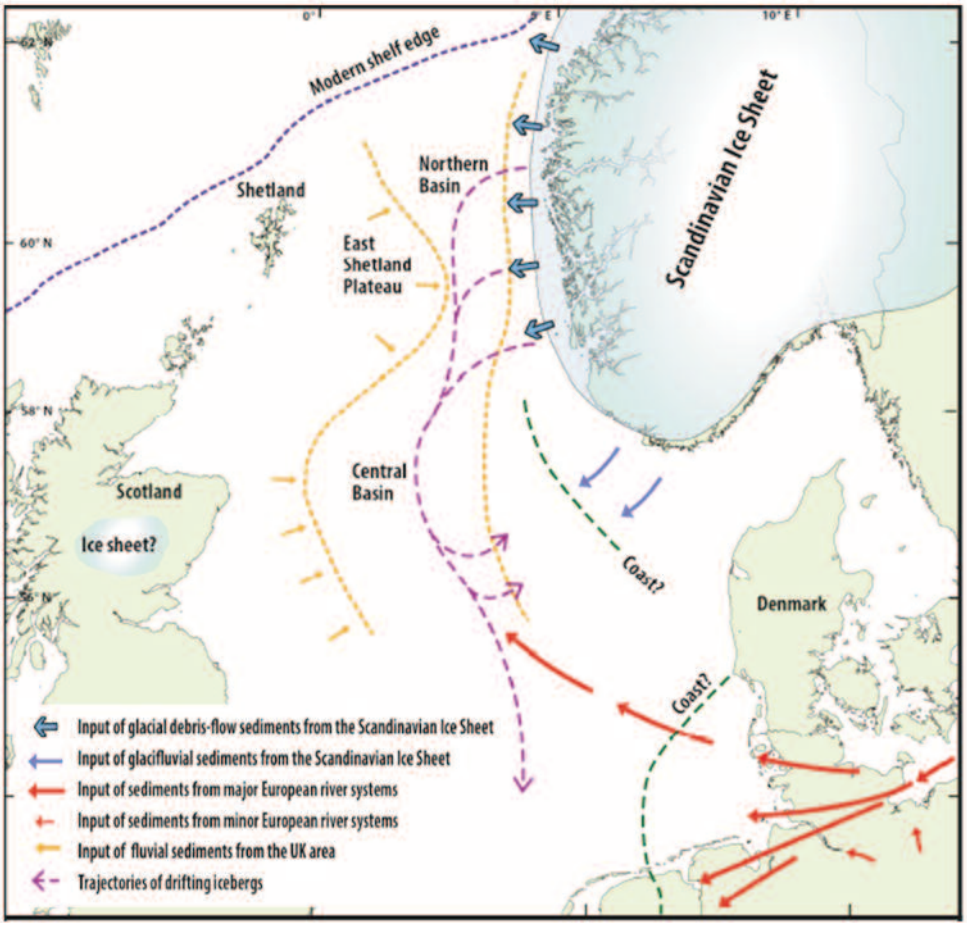
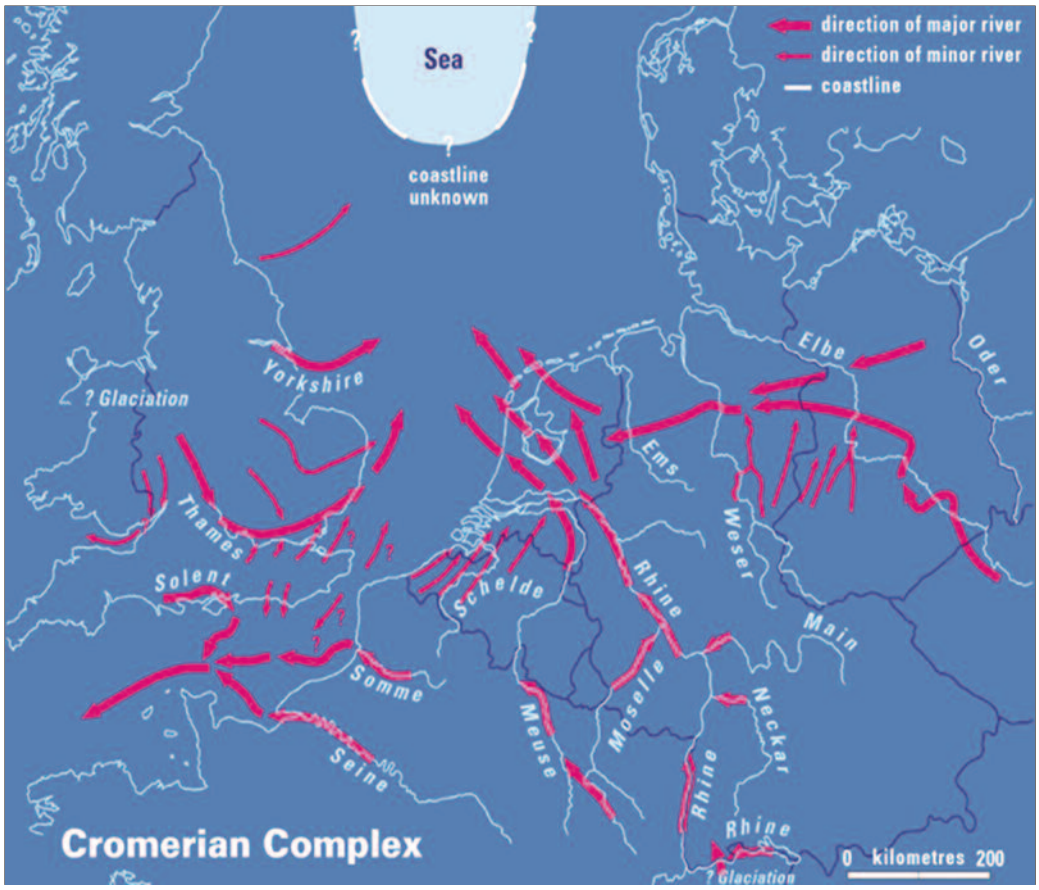


Figure 6 Early Pleistocene glacial evidence in the northern North Sea, off the Baltic River delta front (from Ottesen et al. *2014).*

Figure 7 Drainage and palaeogeography at low-stands during the Cromerian Complex Stage (after Gibbard 1988).



humans (or hominins, as not all were *Homo sapiens*), who were able to colonise our region. For example, two particular sites have been identified on the East Anglian coast — Pakefield and Happisburgh on the Norfolk coast have shown evidence of human occupation in two interglacial intervals between *c.* 600,000 and 750,000 years ago. There may be more sites forthcoming.

In central France, there are sites that could be older: some claimed to be as much as a million years old. Around the Mediterranean, similar aged and older sites are known. This would be the refuge area from which Britain was recolonised in some of the Cromerian Complex interglacials. The major Weald–Artois land bridge or link between the Boulonnais [the central land area in Fig. 8] and Sussex, Kent and south-east England was still an important landscape element during this interval. It is a predominantly chalk ridge, no doubt, carrying its own streams (Fig. 8). In the Chalk, bands of flint occur and where these eroded (cliffs, gravel beaches, river valleys) they provided a rich lithic resource for tool-making hominins.

In Britain, the most important site from this period is Boxgrove, near Chichester in Sussex. The deposits at this site represent an interglacial period, fairly late before the arrival of the ice at *c.* 450,000 years ago. It is especially important since it yielded the earliest find of human fossil bone in Britain to date. The site is associated with a fossil beach complex, which can be identified in Hampshire and on the Isle of Wight. This locality occurred at the mouth or estuary of the Solent River system. Basically, by the Cromerian Complex interval there is evidence of human occupation of the area during the interglacials, although the glacials were probably too cold for human occupation. Almost all these localities are coastal sites, at least as far north as around Britain — the late Cromerian Complex site at Boxgrove along the English Channel, and the earlier Cromerian Complex sites at Pakefield and Happisburgh along the North Sea (Fig. 8).

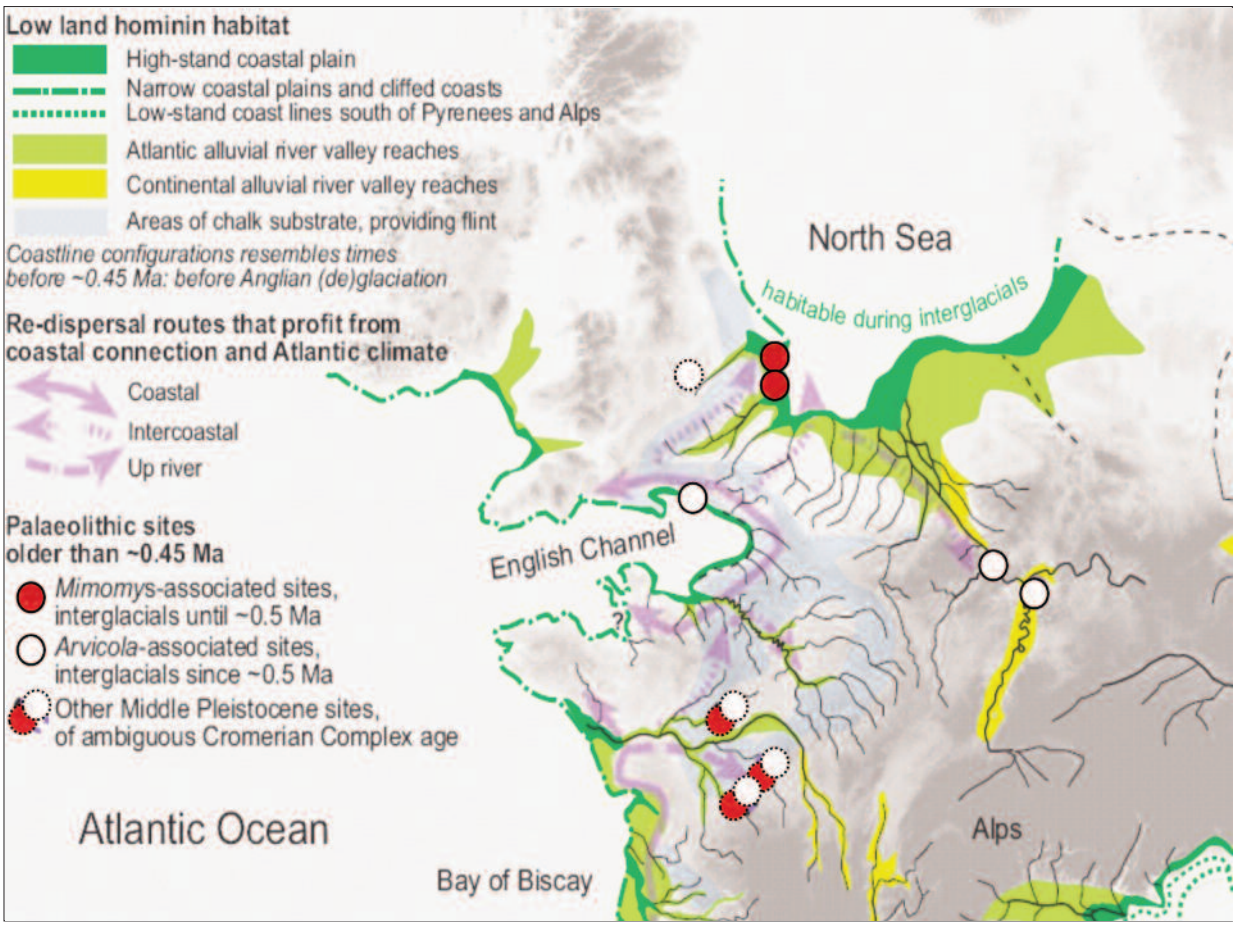

Low land hominin habitat
High-stand coastal plain
Narrow coastal plains and cliffed coasts
Low-stand coast lines south of Pyrenees and Alps
Atlantic alluvial river valley reaches
Continental alluvial river valley reaches
Areas of chalk substrate, providing flint
Coastline configurations resembles times before ~0.45 Ma: before Anglian (de)glaciation
Re-dispersal routes that profit from coastal connection and Atlantic climate
Coastal
Intercoastal
Up river
Palaeolithic sites older than ~0.45 Ma
Mimomys-associated sites, interglacials until ~0.5 Ma
Arvicola-associated sites, interglacials since ~0.5 Ma
Other Middle Pleistocene sites, of ambiguous Cromerian Complex age
North Sea
habitable during interglacials
English Channel
?
Atlantic Ocean
Bay of Biscay
Alps

Figure 8 Coastlines and palaeogeography at high-stands during the Cromerian Compex, including presumed dispersion routes of hominins (after Cohen et al. *2012).*

Channel River, Continental shelf and Ocean floor

When the coastal and emerged seafloor environments of the Channel and North Sea are compared, it is important to understand that the geology of the English Channel is very different to that of the North Sea. The latter is a subsidence area and depocentre (*see* Fig. 4). By contrast, the Channel is floored mostly by Mesozoic and Paleogene bedrock, through which a complex of channels have been incised (Fig. 9, *overleaf*). The largest of these channels is the so-called Northern Palaeovalley. It merges with palaeovalleys of the Somme and the Seine and continues as the joined Median Palaeovalley across the deeper shelf region of the Western Channel. The confluence of all the Eastern river systems was important for incision and river terrace formation of the Southern English and Northern French rivers. At sea-level low-stands, the river entered the Atlantic Ocean between Cornwall and Britany.

From there, the sedimentary system continues as a complex of submarine canyon-like features passing sediment down the continental slope and on to the Bay of Biscay ocean floor, where there are two major abyssal fans. These fans build up as a consequence of sediment delivery down the English Channel and also down the Celtic or Irish Sea. This abyssal record has become known in recent years, since it was cored by our French colleagues (Toucanne *et al.* 2009). The relatively continuous deep-sea records from this area are critical because they provide a direct way to link Marine Isotope Stages (MIS) and pulsed sediment delivery from Britain and the Continent to the abyss. This record reaches back 1.2 million years. It shows increased sediment delivery during the glacials of the Cromerian Complex (even-numbered MIS 22 to 14). Then, from MIS 12 onwards, within glacial periods it shows major extra increases in sediment delivery (amplified amounts), from the Channel River and the shelf edge regions to the abyssal fans. This signals that a critical change occurred *c.* 450,000 years ago: For the first time, we see glaciation right across this whole region, recorded at the very downstream end of the English Channel drainage system. This tipping point in the record marks the first glaciation that directly affected the English Channel and southern Britain. This glacial period is known as the Anglian Stage.

The Anglian, 450,000 years ago: opening of the Dover Strait begins

Critically important sedimentary evidence of the glaciation covering most of Britain *c.* 450,000 years ago exists across East Anglia. The oldest glacial diamicton is the so-called Happisburgh Diamicton (Fig. 10A, *overleaf*). It has a characteristic grey colour, and contains mostly local lithologies and silt derived from the floor of the North Sea. It was deposited by ice that crossed the North Sea. It contains very characteristic crystalline rocks, including, in particular, larvikite and rhomb porphyry, which are erratics derived from the Oslofjord area of southern Norway. During this initial stage of the glaciation the ice rode up on to the British landmass and deposited this material. It is overlain by lacustrine meltwater sediments.

Associated with the diamicton are glacial lake sediments (Fig. 10B). Sometimes these characteristically laminated deposits are called ‘varves’, but technically they are rhythmites, because varves are laid down annually. If it cannot be demonstrated that they were laid down annually, although they are probably annual,

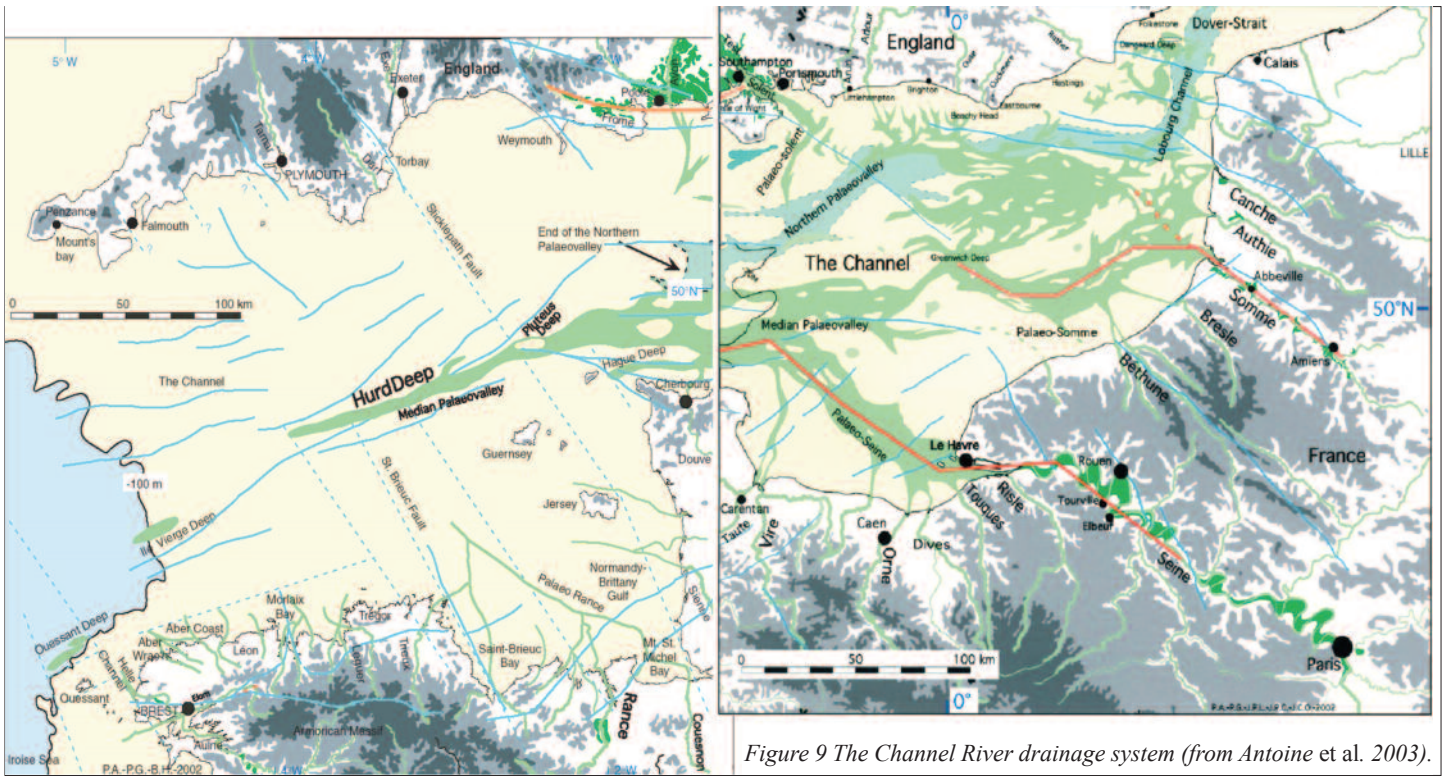
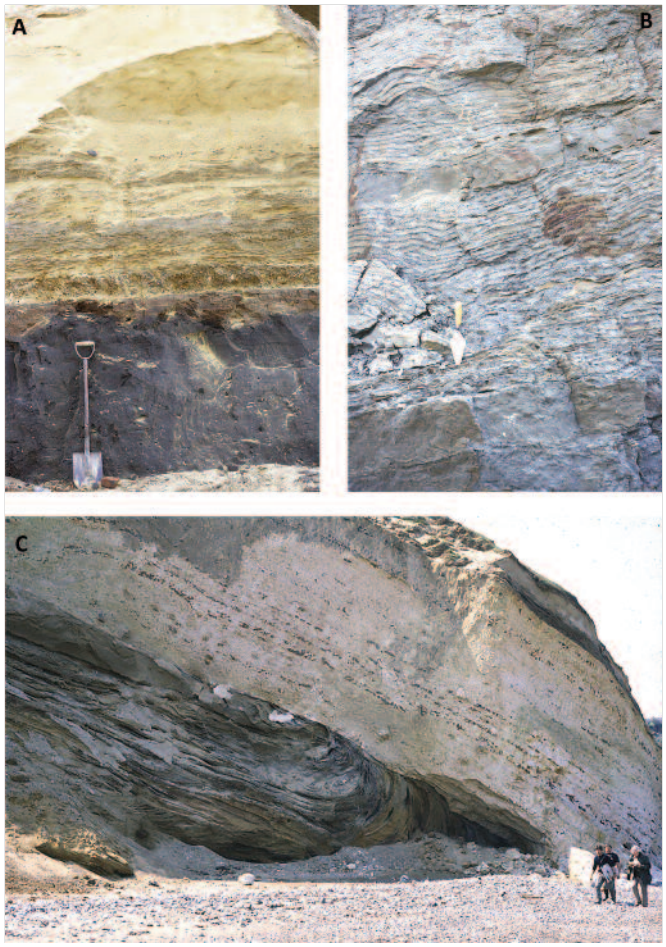


Figure 9 The Channel River drainage system (from Antoine et al. *2003).*

Figure 10 Photographs of glaciogenic deposits of Anglian age from the base of cliff sections at Happisburgh and Sidestrand, Norfolk coast: (A) North Sea Drift Formation, Happisburgh Diamicton Member and overlying outwash sand; (B) Rhythmite (varved) glacio-lacustrine laminated deposits grading to waterlain melt till at the base; (C) Glaciotectonic thrusted block of Chalk (flint banding in place) (spade, trowel, people for scale; photographs by P. L. Gibbard).



the complication is avoided by using the more general term rhythmites, or laminated sediments. Associated with these ice-front, lake-rim sediments are stratified diamictons. Diamicton laid down on the land under a glacier is normally massive. Therefore when a glacial diamicton is stratified, another explanation must be sought. The explanation here is that the diamicton was laid down from floating ice, i.e. its occurrence indicates an ice front terminating in a meltwater-ponded foreland. The wet ice-margin deposition is also accompanied by glacial tectonics, a text-book example of which is the Sidestrand thrust block (Fig. 10C). The direction of overthrusting of this block and many like it in the Norfolk cliffs is an indication of ice advance from across the North Sea and, because of the erratic clasts, likely all the way from Norway.

The advance of the ice sheet across the North Sea produced the inevitable. If all the drainage systems were blocked by ice from Scandinavia entering Britain, the water was prevented from escaping to the sea. The presence of upland topography (Weald–Artois anticline, *see* Fig. 2) between Kent and northern France (*see* Fig. 8) caused an extensive lake to form between the ice sheet in the north and the land barrier in the south. The water-laid deposits from along the ice front at Happisburgh, would be from a north-western corner within the massive lake.

At a lowest point along the southern rim of the lake, it ought to overspill, and this would have happened into what is now the Strait of Dover (*Pas de Calais*). This idea, originally by Thomas Belt (1874, a letter published in *Nature*, and discussed in correspondence between Alfred Wallace and Charles Darwin), explains the major change in palaeogeography seen before and after the Anglian glaciation (Fig. 11, *opposite*), and connects the glacial sedimentary evidence of East Anglia, the geomorphology encountered in the Dover Strait, and that from the abyssal fans off the English Channel.

Just before the proglacial lake ponded and overspill began, the still very similar morphology and elevation of the periglacial chalk landscape of Kent and across to Picardy in France, was

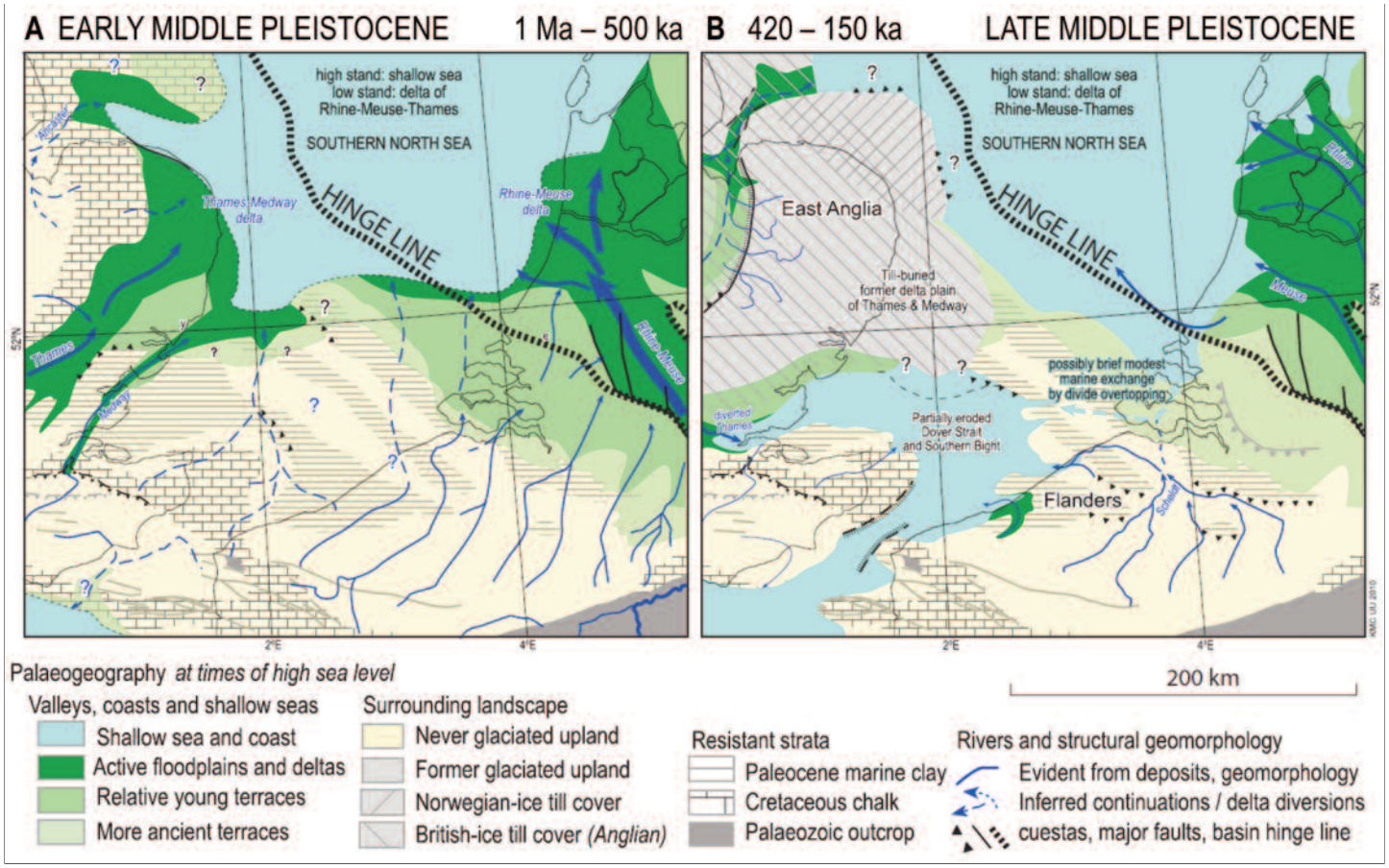


Figure 11 Contrasting palaeogeography (high-stand situations) before and after 450ka (scenario maps from Hijma et al. *2012; Cohen* et al. *2014).*

continuous from Dover to Calais on the two sides of the Strait — also in elevation. A saddle-like topographic feature in the Chalk hill topography, along the drainage divide separating local rivers draining to the north and the south, would have functioned as the sill for the spillage. To the north, the lake maintained a water level held up by the elevation of this saddle. Estimates of its height are tentative — as it is now eroded — but it should be below the lowest such saddles surviving in adjacent Kent and Picardy, and lows in the topography of the Holocene backset cliff section on either side of the channel give some handle on this elevation. Figure 12 (*overleaf*) shows the extent of the Anglian lake, assuming a former Dover Strait saddle at *c.* 30m above present sea level.

Once Anglian lake overspillage set in, it began to erode the chalk ridge, and a spillway channel incised, deepened and widened the saddle. With proceeding erosion, the saddle position retrograded northward and at some point in this process, it no longer was held up by Chalk, but by the younger Paleogene deposits such as the London Clay. The bedrock geology of the stripped floor of the Strait of Dover today indicates the location off Belgium, where the retreating saddle would have changed substrate. Projecting the seafloor geology (at 30m to 50m depth today) upwards to the level of the former saddle and the modern cliff tops, indicates some 70m of Chalk bedrock to have been eroded since the Anglian began, more than some 32km wide. Similarly, some 45m of Paleogene 'bedrock' has been eroded, more than 180km wide — representing an even larger volume. Such quantities of sediment are not found in the North Sea deposits to the north, and therefore the majority must have been evacuated southward, via the Channel River and ended up in the lower shelf, shelf front and abyssal fans.

The Saalian (Wolstonian), culminating 160,000 years ago: opening of Dover Strait completed

Importantly, this dramatic erosion of the Strait of Dover area is not thought to have taken place during one, but during two major episodes of glacial erosion. In the first, 450,000 years ago and associated with the Anglian glaciation, substantial erosion took place there, but time was insufficient for removal of all the bedrock ridge structure. This is the reason why a remaining land bridge, which the sea levels during the interglacials after the Anglian (such as that of the Hoxnian, *see* Fig. 1) could hardly overtop, is depicted in the scenario maps in Figure 11. It took a second major glaciation of the southern North Sea, rivalling that of the Anglian in extent (Fig. 13, *overleaf*), to form a proglacial lake again, restarting the retrograding proglacial erosion process, and finishing the job of fully connecting the North Sea and English Channel drainage.

This second event occurred 160,000 years ago during the glaciation termed Wolstonian in Britain and Saalian in the Netherlands (within MIS 6; *see* Fig. 1). During this phase, British ice lobes reaching as far south as the Fenland in eastern England met once again with Scandinavian lobes coming down across the North Sea. On the Dutch side of the North Sea Basin, the Saalian glaciation reached farther south than any glaciation before (what the Anglian glaciation did on the British side). It reached a maximum limit across the centre of the country almost to the River Rhine, which formed an ice-marginal stream of the Saalian ice sheet (just like the Anglian ice did with the Thames).

An important indication that at the beginning of the Saalian glaciation a topographic ridge still existed across the southern North Sea to the south of the ice-front are the contemporaneous

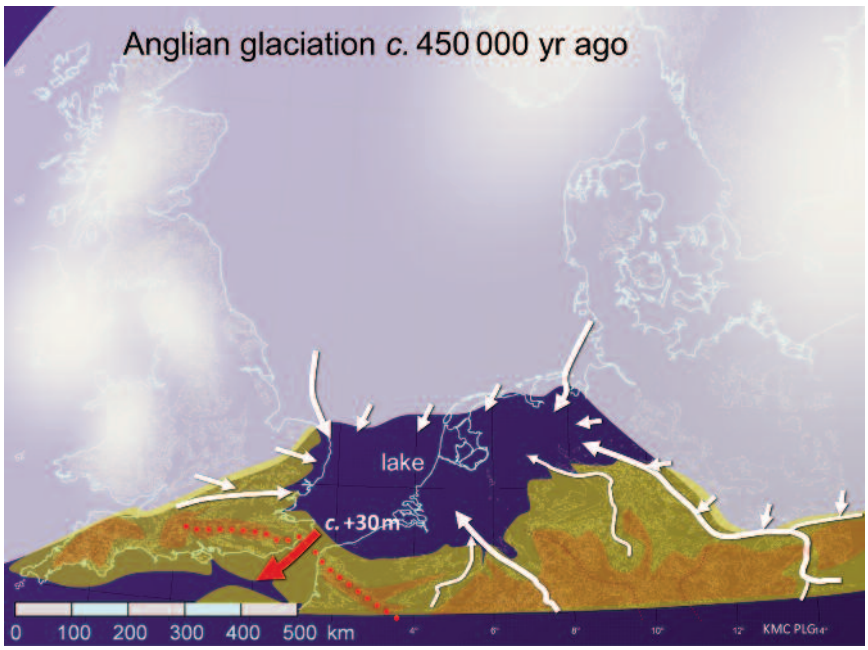


Figure 12 Proglacial lake extent as envisaged for early stages of the Anglian, leading to initial breaching of the Strait of Dover (after Gibbard 1995; Cohen et al. *2005; Gibbard 2007; Cohen* et al. *2014).*

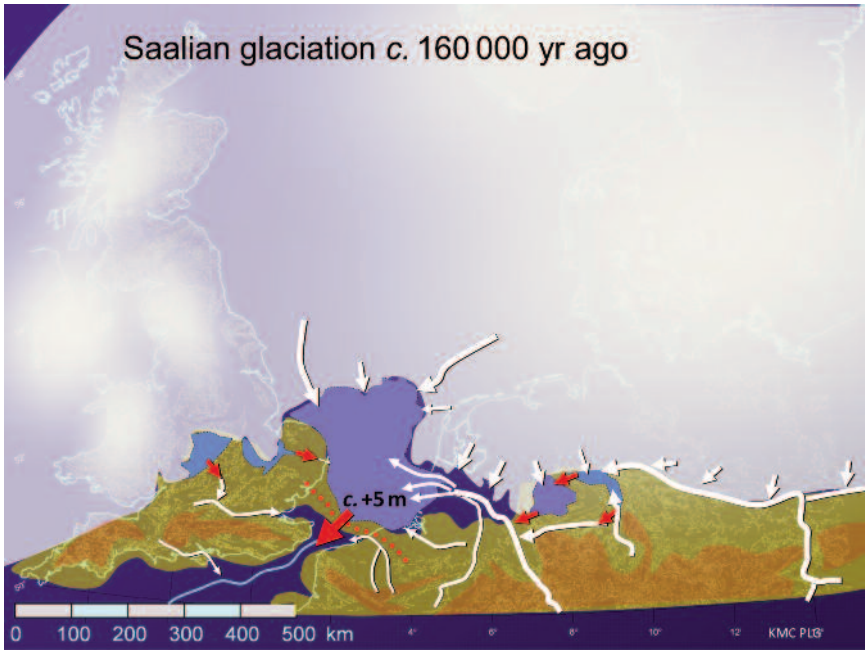


Figure 13 Proglacial lake extent as envisaged for the Drenthe Substage of the Saalian, completing the breaching of the Strait of Dover (produced for OUGS symposium and for this publication, to complement Fig. 12; it incorporates reconstructions for the Saalian ice front from Busschers et al. *2008 (Netherlands); Meinsen* et al. *2011 (Germany), Moreau* et al. *2012 and Hijma* et al. *2012 (southern North Sea) and from Gibbard* et al. *2009 for the Wolstonian of East Anglia).*

braided-river deltaic features from the ice-marginal River Rhine. This delta must have formed in a standing body of water, so there is evidence for a proglacial lake. The elevation can be traced in the geological mapping of the western Netherlands, and grades to a base level estimated at *c.* +5m (after accounting for background subsidence in this part of the basin, e.g. *see* Fig. 4). By coincidence, the Saalian ice-lake delta terminates near the present coast. Dissecting features from subsequent stages signal effective base levels at least 10m deeper, showing that erosion quickly proceeded. These can be traced across the North Sea floor (*compare* Fig. 11B with Fig. 14A). Mapping of the North Sea floor between the Netherlands and Britain has recently been updated using seismic geophysical methods, showing the Saalian ice-limit and showing clinoforms next to it, from glacial outwash deltas into the same lake (at comparable depths of preservation as the Rhine lake delta). Also, the abyssal record off the English Channel continental slope shows a sediment delivery peak in MIS 6 (at *c.* 160,000 years ago) that rivals that of MIS 12 (at *c.* 450,000 years). All of this is strong evidence for the contemporaneous occurrence of a lake during maximum glaciation Drenthe Substage in the Saalian (and equivalent part of the Wolstonian).

If the Saalian and Anglian ice lakes are compared, there are differences in the precise positions of the ice limit, and there is a difference in the elevation to which each lake would fill and spill over. Despite this, essentially the Saalian spillway erosion is envisaged to have continued where Anglian overspillage had stopped.

That erosion of the land bridge stopped suddenly towards the end of the Saalian is found in two particular characteristics. The first is that the ice-lake would have no longer used the southward spillway, as soon as the Scottish and Norwegian ice masses up north were no longer coalescent. At that point in the deglaciation history of the Anglian, the North Sea ice lake would have quickly drained northward, rapidly dropping the lake level and exposing a good part of the former proglacial lake floor as dead-ice terrestrial landscape. The second characteristic is the diversion of the River Thames, caused by expanding British ice lobes in the Anglian following deposition of the Happisburgh Diamicton. These glacial events over Essex and Suffolk positioned the new Thames Valley south of where the saddle would survive, and covered up pre-diversion valley pathways across the land bridge with considerable thickness of 'Lowestoft Formation' tills (*see* Fig. 11B). The two events together explain that once Anglian lake spillage ceased, there was no substantial post-Anglian river system that kept the land bridge under attack. So, during the second major glaciation, some 300,000 years after the first, proglacial spillway erosion could resume and finally destroy the remnants of the land bridge and fully connect the North Sea to the English Channel.

A last important difference to note is that in composition and erodibility the saddles holding up the Anglian/Elsterian and the Saalian lakes are not comparable. The land bridge present in Saalian/Wolstonian was much lower and narrower than that during the Anglian. It was no longer made of Chalk, but of London Clay (or similar Tertiary sediments). The ridge was therefore more easily eroded. It is likely that the final stages of the destruction of this land bridge were really rapid and potentially dramatic. The lake may have not simply drained, but flushed out southward into the Channel River. There is good geomorphological indication for a catastrophic magnitude of this

event in Gupta *et al*.'s 2007 paper in *Nature*. This shows detailed bathymetric mapping of the English Channel in which a deeply incised channel (the Northern Palaeochannel) includes streamlined islands cut into Chalk bedrock. The islands are streamlined with some younger drainage carved into them. This morphology indicates very fast flowing water, which almost certainly resulted from the breaching of the last remaining part of the land bridge, producing very fast erosion. Finding other than geomorphological evidence in the English Channel is difficult because it has all been stripped of sediment.

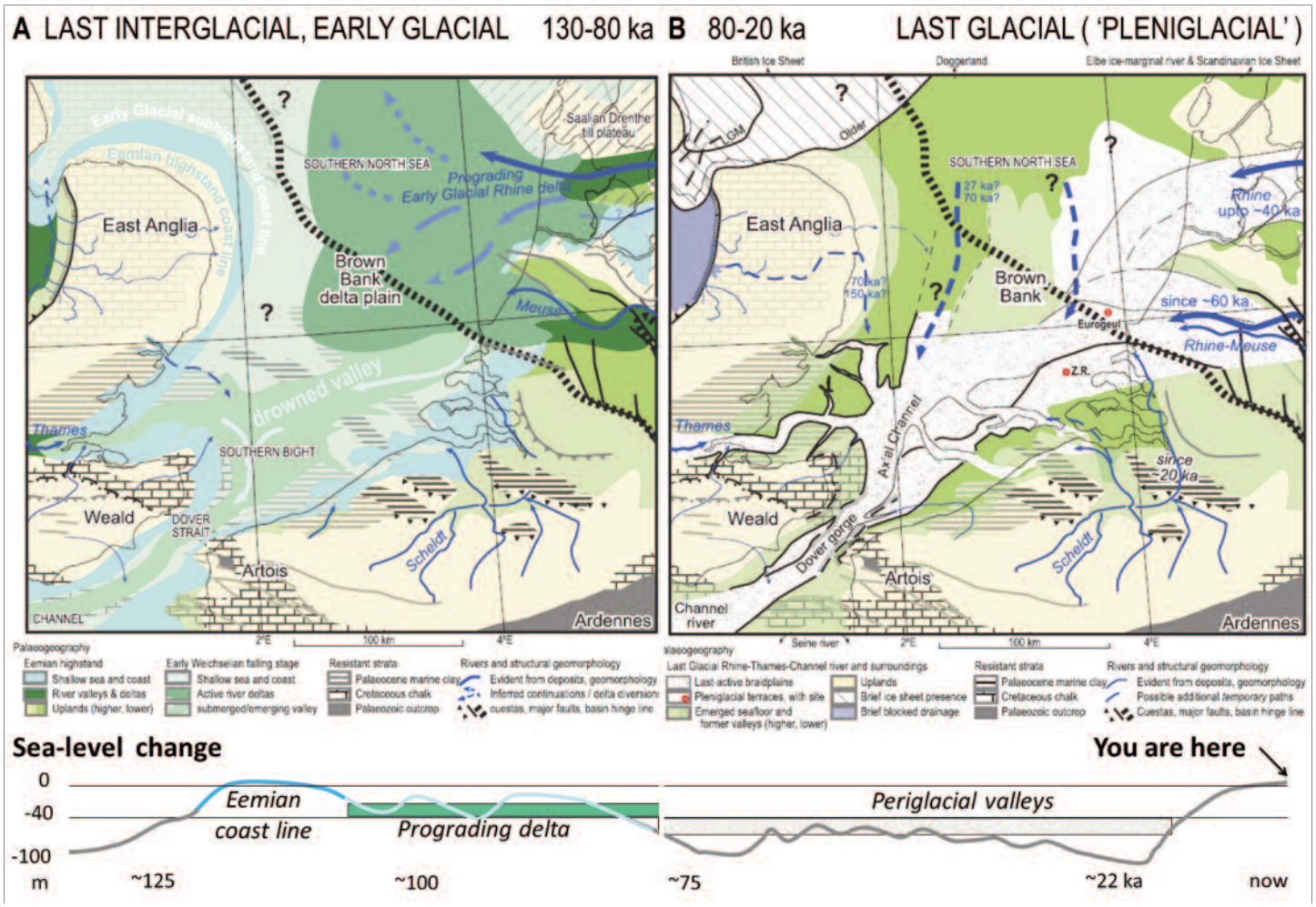
So, there was potentially a catastrophic flood, but this is not the principal point in this review. The main point is that the full opening of the Strait of Dover is the result of major big glaciations, with two proglacial lakes in the Anglian and in the Saalian/Wolstonian phases. Each of them must have existed for perhaps 5,000 or 10,000 years, during which time excess water gently spilled over the bounding barrier, before that barrier was finally removed. It is interesting to note that the cold periods between the Anglian (Elsterian) and Wolstonian (Saalian) (i.e. MIS 10 and 8) seem to have been characterised by less-extensive glaciation, the drainage of the southern North Sea region apparently remaining unmodified throughout this interval.

The opening of the Strait of Dover is portrayed as a story of glacial erosion, in the absence of man, but it is linked to the interglacial situations that are of great importance to the Palaeolithic archaeologist. From *c.* 800,000 years ago, episodic human occupation of the region had begun. At that time the land bridge provided a crucial link between what is now Britain and what is now the Continent. In the time between the Anglian and Saalian glaciations — 'the interbellum' — humans were also present in the region, while the land bridge had altered but, critically, not disappeared. Different paths for migrations and access to lithic resources were available to humans after the Anglian than were available before it (*compare* Fig. 11B to Figs 8 and 11A).

The Late Pleistocene, Holocene, and future: aftermath of the opened Dover Strait

Following the Saalian glaciation, the Last Interglacial began *c.* 130,000 years ago. This was the first time that the Southern Bight of the North Sea had a coastal outline that is comparable to that of the Holocene. Last Interglacial humans (Neanderthals at this stage of human evolution in our area) occupied continental Europe, but no humans appear to have been living in England. This was because they were unable to cross the seaway that, in this interglacial, first formed a significant barrier. Although the Last Interglacial was relatively short (*c.* 12ka, the sea-level high-stand lasting just *c.* 6ka), it was followed by slow sea-level fall with the Rhine delta building out into the North Sea (Fig. 14). As the sea-level fall proceeded into the last glacial, finally the first glacial occurred where a river larger than the Thames passed through the Dover Strait for the entire duration of the sea-level

Figure 14 Palaeogeography during the last glacial cycle, sea-level high-stands in the first half, and sea-level low-stand in the part after 80ka (scenario maps from Hijma et al. *2012; tentative sea-level curve for the periods added by the authors).*



low-stand (*c.* 100 ka). This Rhine-Thames river made use of a gorge-like valley that it had inherited from the Saalian glaciation. During shorter periods within the Last Glacial, meltwater from British and Scandinavian ice fronts well to the north of the study area would also have spilled south towards the study area, but this was probably only episodically, and for most of the time that outwash drained north. If we disregard the brief episodes of maximum glaciation and ignore periods of sea-level high-stands, then it is already 450,000 years ago that the Thames became connected to the Channel River, but it is only 130,000 or so that the Meuse and Rhine did so.

Now, what about the future? When a next glaciation, with ice coverage comparable in coverage to that of the Anglian occurs, no glacial lake will be formed. The North Sea and the Channel of the future will certainly look different from today; how different will depend on the erosion and deposition around our coasts. For example, the Dover Strait might be expected to be progressively widened by erosion during sea-level high-stands.

The final critical point is that this presentation is entitled 'Quaternary evolution': ice ages come and go, climates oscillate between cold and warm, and vegetation migrates and more or less regenerates in each interglacial. However, what is not the same is the landscape, because there is erosion as well as deposition during each glaciation, the effects of which are not repaired in non-subsiding areas. The landscape of the future will be inherited from our situation today and its evolution will proceed from there. The Strait of Dover provides graphic evidence of this.

Acknowledgements

The OUGS lecture, on which this text is based, was transcribed by Dick Millard. The authors wish to express their gratitude to him for his efficient work. They also thank the OUGS for the opportunity to publish this summary paper, as an entry point to the peer-reviewed literature on the subject.

References

Antoine, P., Coutard, J. P., Gibbard, P., Hallegouet, B., Lautridou, J. P., and Ozouf, J. C. 2003 'The Pleistocene rivers of the English Channel region'. *J Quaternary Sci* **18**, 227–43

Belt, T. 1874 'Glacial Period'. *Nature* **10**, 62–3

Busschers, F. S., Van Balen, R. T., Cohen, K. M., Kasse, C., Weerts, H. J., Wallinga, J., and Bunnik, F. P. 2008 'Response of the Rhine–Meuse fluvial system to Saalian ice-sheet dynamics'. *Boreas* **37**, 377–98

Cameron, T. D. J., Crosby, A., Balson, P. S., *et al*. 1992 *United Kingdom Offshore Regional Report: The Geology of the Southern North Sea*. London: British Geological Survey, HMSO

Cohen, K. M., Gibbard, P .L., and Busschers, F. S. 2005 'Stratigraphical implications of an Elsterian proglacial "North Sea" lake'. Bern (Switzerland): abstract booklet SEQS meeting

Cohen, K. M., MacDonald, K., Joordens, J. C. A., Roebroeks, W., and Gibbard, P. L. 2012 'Earliest occupation of north-west Europe: a coastal perspective'. *Quaternary International* **271**, 70–83

Cohen, K. M., Gibbard, P. L., and Weerts, H. J. T. 2014 'North Sea palaeogeographical reconstructions for the last 1 Ma'. *Netherlands J Geosci* **93**, 7–29

Gibbard, P. L. 1988 'The history of the great north-west European rivers during the past three million years'. *Philosoph Trans Roy Soc London* **B318**, 559–602

Gibbard, P. L. 1995 'Formation of the Strait of Dover', *in* Preece, R. C. (ed.) *Island Britain — a Quaternary Perspective*. London: Geol Soc Special Publ **96**, 15–26

Gibbard, P. L. 2007 'Europe cut adrift'. *Nature* **448**, 259–60

Gibbard, P. L., and Cohen, K. M. 2008 'Global chronostratigraphical correlation table for the last 2.7 million years'. *Episodes* **31(2)**, 243–7

Gibbard, P. L., Pasanen, A. H., West, R. G., Lunkka, J. P., Boreham, S., Cohen, K. M., and Rolfe, C. 2009 'Late Middle Pleistocene glaciation in East Anglia, England'. *Boreas* **38**, 504–28

Gupta, S., Collier, J. S., Palmer-Felgate, A., and Potter, G. 2007 'Catastrophic flooding origin of shelf valley systems in the English Channel'. *Nature* **448**, 342–5

Hijma, M. P., Cohen, K. M., Roebroeks, W., Westerhoff, W. E., and Busschers, F. S. 2012 'Pleistocene Rhine–Thames landscapes: geological background for hominin occupation of the southern North Sea region'. *J Quaternary Sci* **27**, 17–39

Lisieki, L. E., and Raymo, M. 2005 'A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records'. *Paleoceanography* **20**, PA1003, 10.1029/2004PA001071

Meinsen, J., Winsemann, J., Weitkamp, A., Landmeyer, N., Lenz, A., and Dölling, M. 2011 'Middle Pleistocene (Saalian) lake outburst floods in the Münsterland Embayment (NW Germany): impacts and magnitudes'. *Quaternary Sci Rev* **30**, 2597–625

Moreau, J., Huuse, M., Janszen, A., Van Der Vegt, P., Gibbard, P. L., and Moscariello, A. 2012 'The glaciogenic unconformity of the southern North Sea', *in* Huuse, M., Redfern, J., Le Heron, D. P., Dixon, R. J., Moscariello, A., and Craig, J. (eds) 2012 *Glaciogenic Reservoirs and Hydrocarbon Systems*. London: Geol Soc Special Publ **368**, 99–110; http://dx.doi.org/10.1144/SP368.5

Ottesen, D., Dowdeswell, J. A., and Bugge, T. 2014 'Morphology, sedimentary infill and depositional environments of the early Quaternary North Sea Basin (56–62ºN′). *Marine Petroleum Geol* **56**, 123–46

Toucanne, S., Zaragosi, S., Bourillet, J. F., Gibbard, P. L., Eynaud, F., Giraudeau, J., Turon, J. L., Cremer, M., Cortijo, E., Martinez, P., and Rossignol, L. 2009 'A 1.2 Ma record of glaciation and fluvial discharge from the West European Atlantic margin'. *Quaternary Sci Rev* **28**, 2974–81

Westerhoff, W. E. 2009 *Stratigraphy and Sedimentary Evolution: the lower Rhine-Meuse system during the Late Pliocene and Early Pleistocene (southern North Sea Basin)*. TNO Geological Survey of the Netherlands, Utrecht, Geology of the Netherlands **2**, 1–168

Ziegler, P. A. 1978 'North-west Europe: tectonics and basin development', *in* van Loon, A. J. (ed.) *Keynotes of the MEGS-II (Amsterdam 1978), Geologie en Mijnbouw* **57**, 589–626

Summing up by OUGS President

Dr Tom Argles

(Senior Lecturer in Earth Sciences, The Open University)

[OUGS Canterbury Symposium: Marine Geotales; original transcription by Norma Rothwell from the seminar recording; edited by Dr Argles and POUGS Editor David M. Jones]

Bearing in mind that I am a hard-rock geologist, this couple of days has been somewhat of a revelation to me and it has definitely been a reawakening of concepts, facts and knowledge that I had buried very carefully in the back of my career and hadn't visited at all for some years. But it has helped me to learn a lot, particularly about sedimentology, soft rocks, quaternary geology and geomorphology. I hadn't thought about that for decades, really, in any meaningful way, so it has been really nice to catch up with some of the cutting-edge stuff and up-to-date research that has been going on and I would like to thank everyone who has been a part of it.

Introductory Lecture

'Tales from the deep blue sea: detecting Earth processes from marine sedimentary deposits'

Dr Angela Coe (Open University)

I wasn't here on Friday night, but I understand that Angela Coe gave an excellent talk. I am hedging my bets here, but I reckon that she probably talked about oceanic anoxia, the PTM and possibly molybdenum isotopes — this is really a wild punt in the dark, but it seems a real possibility that that was the case. I hope that you all enjoyed that talk and I am sure that you did.
[Dr Argles is 'not wrong'. Because most of the research presented by Dr Coe is to be published imminently in other periodicals, we honoured her request not to record her lecture — Ed.]

'Holocene evolution of the southern North Sea'

Dr Peter Balson (BGS and OU Tutor)

So we move on to Saturday morning, when my train deposited me at Canterbury. I had to catch that rather early in the morning so I whipped up here and arrived just in time to catch most of Peter Balson's talk about the North Norfolk Banks. This was immediately rather interesting to me. Partly because I was expecting a totally different talk from the order sheet that I had been given, but also because I had just had a family holiday in North Norfolk so I had a vague orientation, a sense of where I was, and I paraphrased this talk [in my notes] as 'Where did the sand come from?' I am not sure that I am really qualified to answer that. It seems that there is an awful lot of sand out there — really too much sand — and that the actual sources of that sand are still very much up for debate. Also the sand has been sitting there for quite a long time and essentially it has just been shifting around and changing form for a number of thousands of years. So there were some lovely bathymetries and images of the seafloor and the features forming on that. I really liked the bathymetric and seafloor images we saw. One of the things that Peter concentrated on was the internal structures and the features of those banks, and that [these features] seemed critical to their origin and their development. That really brings us back to the kind of field day that we have had today [Sunday morning], looking at those structures that you can observe in the field, in cliffs and in exposures. It is nice to know that the internal and macro structure of those features is very, very important in determining how we understand these kinds of geological features.

'Did the sea taste salty to the dinosaurs?'

Dr Christopher Pearce (University of Southampton)

The next talk was by Chris Pearce, which again was a slight surprise to me. It was very nice to see Chris again because I knew him as a PhD student at Walton Hall. I was sort of hoping that I would be able to get this summary down to be a little shorter and so I paraphrased his talk as 'Where Does the Salt Come From?'. And I was going to leave it at that; but suffice it to say that he managed to weave in contributions from such diverse features as processes of volcanoes, rivers, hydrothermal processes, peridotite weathering and dolomitisation. It was a wonderful talk. It sort of drew the whole of Earth's System into a holistic look at where the salt comes from in the ocean. As I said, I learned a lot of things and one of them was that it is pretty much the same composition of salt all across the oceans at the moment, but that it has changed through time. That was a real revelation to me. I kind of assumed that seawater wasn't the same everywhere and that it would have variations that were quite significant in terms of space. Chris assured us that this wasn't the case and that it was very consistent on a certain time level. However, when one goes back in time, that is when it changes. That was a very interesting point to make.

'Bubbles in the ocean: how a tiny bubble can matter for a planet'

Dr Helen Czerski (University College, London)

The next talk was an interesting and very effervescent talk, I thought. You could really see some of the gloss of the BBC on Helen, I think, so there are an enormous number of sound bites that I could have picked out, but there are a few things that I really liked. The idea of the oceans breathing — I really love that as a sort of concept to bring across — the idea of the exchange of gases across the interface. Her description of her research is that of 'The Science of Finding k', which, for somebody as mathematically challenged as I am, was a real relief. That she could bung all these really complicated processes into one letter is the kind of equation that I can really cope with. I note also that there are almost no pine trees in the mid-Atlantic, which I thought was a very useful point to pick up on. And she pointed out also that it is very wrong to throw 'boys' off the back of a boat; I was quite relieved to hear that. Interesting, too, is her idea of changing scales, which is a real theme with geologists, as they

© OUGS ISSN 2058-5209

are constantly slipping between scales, between the very, very large scale and the very, very small scale. And I did like the quotation that she dragged up from *The Lord of the Rings*, which is from Treebeard, one of the Ents (or tree folk) in the Hobbit series, when the hobbits were running around them trying to get things done, saying, "That doesn't really make any sense to me, but then you are very small."

'What lies beneath: offshore data acquisition and what it can do for your science'

Miss Heather Stewart (BGS, Edinburgh)

Heather was flipping across scales very effectively in her talk too; so she started off with some sweeping verbal images of seafloor bathymetry and the original maps of the seafloor that were brought out in the 1970s, and the sort of images that we have all had since. Then focusing right, right down with the much higher resolution that we have today, to a centimetre-scale of coral on the walls of [submarine] canyons, which was really, really nice. So much seafloor is only now being mapped in that kind of detail. For several decades we have had the sort of broad-brush aspect of the whole global ocean floor/sea floor, which is very much related to plate tectonics. It is really only now that we have got multi-beam sonar and so [with that can] pick out the much finer details that enable to us to understand features that are more related to geomorphology and to sedimentology. I am glad that I wasn't one of those guys with a plumb weight on the end of a rope sailing around North West Scotland in all sorts of weather trying to find out how deep the water was!

'A typology for hazards and risks as vectors of change and the implications for integrated management'

Prof. Mike Elliott (Institute of Coastal and Estuarine Studies, University of Hull)

Then we moved on to Mike Elliott. Again it was a very engaging talk about hazards and risks in coastal management. This was extremely topical, as with most of the talks here, which have all had a real topicality to them. So with all the flooding that has been going on recently, together with coastal erosion and landslips, there was a very real topicality to his talk, I thought. One of the things I learned from his talk was to think of the environment in terms of pathology and diagnosis and prognosis. The idea to think of the ocean as being a living organism, almost, and to compare it to a person being treated by a doctor: I thought that was a nice analogy. Also his neat breakdown of what we do to the environment in a sort of tripartite sense of stuff we put in, stuff we take out and other stuff beyond our control, which was really nice — a touch of Donald Rumsfeld about it, if you know that quote.

'Petroleum exploration of extensional basins'

Prof. Alistair Fraser (Imperial College London)
[In communication with Dr Argles — Ed.: "The President unforgivably omitted this summary on the day, due to what he describes as a 'technical notational error'. This transgression is rectified — at least in print — below."]

Al Fraser's tour of arctic petroleum fields was fascinating, not only from a geological standpoint, but also for the political perspective he provided as well. I particularly appreciated the polar map projections, giving an unfamiliar view of the arctic region and revealing geological features that most of us, I suspect, saw with entirely fresh eyes. We get so used to the conventional map views that they become a comfortable, robust framework for our understanding. These polar maps transformed that framework and opened up a whole new context, crowded with questions and problems. Then, jostling cheerfully alongside these new views of the geology were a host of provocative issues — political, economic, social and environmental — that helped to spice [up] the story and made for a highly entertaining and thought-provoking talk. Professor Fraser also sprinkled his presentation with asides and anecdotes that gave tantalising hints of insider knowledge, the feeling that he was letting us in on the facts behind the spin. And all this with no noticeable sign of jet-lag!

'A coastal tour of Kent's geology'

Mr Peter Golding (WEA and University of Kent)

The final talk yesterday [Saturday] — rather like this summing up — was a whistle-stop tour of the Kent coast. What that served to do for me was make me really annoyed that I didn't bring any field boots or clothes with me and so I didn't really feel that I could go on any field trips this morning [Sunday]. But this talk was a wonderful cornucopia of what I might have seen. I understand that you even managed to see all of this without any rain! Astonishing, and so that was really good. It started off slightly sneakily *outside* Kent with a location in East Sussex, but we will gloss over that. One of the things that really impressed me was the history of Romney Marsh. I knew that Romney Marsh and Dungeness and all that area had been reclaimed from the sea, that it had all originally been below the sea. But I had never really followed the history through, so it was a fascinating story that he developed there. I also learned what hassocks were — I am not sure that I really know what they are now but I gather that they are not something that a choirboy wears, which was useful. (That is a cassock – I am aware of that now so I have learned something useful.) I also learned that if you want a job for life you go to Dungeness, buy yourself a lorry and you get a contract from the local council to pick up shingle from one part of the beach and bring it back to where it came from. That was a really nice story too.

Then we had the dinner last night, which I hugely enjoyed and the ceilidh, which I enjoyed too, although possibly slightly less. But I am sure everyone else there did enjoy it. What I did like was the name of the group/band that played: The Royster Catchers — voice from the audience: "They come from Whitstable". Response from Tom, "I grew up in the North West so Whitstable means little to me." — I have learned something else.

I peeled myself out of bed this morning [Sunday] just about in time for breakfast along with those ready to go on the field excursions.

With those remaining on campus I had a very good session in one of the labs with the microscopes, which I enjoyed a lot — doing some demonstrating. It was a bit of nostalgia: remembering learning microscopy at university while I was studying there, and then demonstrating it while I did my PhD, and helping undergraduate students at various universities with microscopy.

'Tsunami hazards — learning from recent events'

Prof. Dave Tappin (BGS, Keyworth)

Then we come to a talk that I have sort of subtitled 'The Cruel Sea', which I thought was rather nice. I did like his idea of pulses of the ages of tsunamis. I think Dave slightly sidestepped that question, although clearly it is something rather current. I was reminded of an idea that I have heard, from probably 20 years ago or even more, that major earthquakes come in clusters at the time of the turn of the century. This was born of the San Francisco earthquake in 1906? — is that right? *[Yes, spot on! Ed.]* — and of a very big one in Japan at a very similar time. So this idea came to be around that time, particularly as the 20th century progressed towards its end and people were looking back, or tracking back and thinking, "Oh no — we are in for it now as this is a problem time." And to a certain extent those predictions have kind of come true in that there have been a number of really large earthquakes around the turn of the 20th century and the beginning of the 21st. I wonder if this is partly related to the idea of an 'Age of Tsunamis', because as Dave pointed out very neatly, tsunamis are very intimately related to earthquakes. I learned that they form by a displacement of crust caused by an earthquake, or that they are triggered by the landslides associated with earthquakes, or that the landslips and slopes are generated below the oceans commonly in the vicinity of major eruptions.

That was a really nice talk, which I enjoyed very much and one of the things that he pointed out was the value of data, particularly the data we have been talking about, i.e. bathymetry and imagery of the seafloor; also of the importance of early warning systems, which enable us to better understand why these tsunamis might be happening. Why, for instance, that lovely example from northern Japan occurred, where there was a rather unexpected fall of the biggest wave in the northern part of the island, which really wasn't exactly where the epicentre of the earthquake was. So that might be a combination of the rupture of the earthquake and the slumps very shortly afterwards that triggered landslips that caused a secondary sort of tsunami that merged into one. A cautionary tale in a way, of not sticking too closely to models, saying, "Yes, we have modelled it now and plotted these things on a graph so we know how it happens."

'Quaternary evolution of the North Sea and English Channel'

Prof. Phil Gibbard (Cambridge Department of Geography) and Dr Kim Cohen (University of Utrecht)

I am getting some very frenetic signals from the side of the stage so I guess that I am going to have to wind up shortly! Fortunately I am on to the last talk so this was Phil's and Tim's talk at the end. I always enjoy a good palaeographic map, although I tend to go back into the Proterozoic rather than to the Pleistocene. But still that was very interesting. We now know about the formation of the Dover Strait and whether that was good or bad, or just a natural process with no moral connections at all — you can judge for yourselves. I was really intrigued to find out that the Baltic Sea used to be a river basin — that hadn't occurred to me at all. Also that the southern North Sea was a lake, one of these dammed glacial lakes, which I thought was a fascinating story. I had heard of similar things in the Himalayas, for example, and also in North America where there existed a huge glacial lake that was dammed in a very similar way and which I have been researching recently, partly for some course material that I have been writing over the last couple of years. That chimes very closely with this idea of a huge body of water being ponded back by a really quite narrow strip of land, which was then eventually breached, eroded and swept away. Similarly, stretches of the geomorphology that Tim showed towards the end were very similar to features in North America, which were related to a similar sort of flood.

So that brings me — rather abruptly — to the end of this summing up. And I'm afraid I now really must go and catch my train!

Book review

Roberts, Neil 2014 *The Holocene: an Environmental History* (3rd edn). Oxford: Wiley Blackwell (hardback ISBN 978-1-118-71257-3, paperback ISBN 978-1-40515-521-2; 364pp; companion Website: www.wiley.com/go/roberts/holocene; hardback £64.65 (variable), paperback £25.38; also available as a download)

Aimed at undergraduates, but suitable for non-specialists, this book covers a wide range of scientific disciplines. Covering the last 10,000 years, it looks at how climate changed, the effect it had on the people/environment interaction, and the development of civilisation. The Introduction sets the scene and makes the point that since the first edition was published in 1986 we have moved from the Holocene to the Anthropocene!

The chapter on 'Reconstructing Holocene Environments' explains the techniques used, and the importance of, accurately dating environments. There are 'Technical Boxes' scattered through the text that explain the more technical aspects of methods used to obtain data: limnology, tephrochronology, etc.

The chapter headings give a good indication of the topics covered by this book: 'The Pleistocene', 'Early Holocene adaptations', 'The first farmers', 'The taming of nature', 'Cultural evolution', 'The impact of modern times', 'The environmental future'.

From the website you can download copies of the figures, tables and technical boxes, which are referenced by chapter. Some files are .pdf files, others are PowerPoint files. There is, however, nothing on the site that is not in the book.

All the sections are very well referenced, making this a good book for serious research or to dip into a particular area of interest to the reader. For a reference work it is surprisingly easy to just sit and read, which I did, and found it interesting through to the last page. I particularly liked the way a wide range of ideas and disciplines were brought together to form a coherent thread throughout the book.

— Lyn Relph BSc (Hons)

OUGS Field Trip Reports

The Ballantrae ophiolite complex, Ayrshire, Scotland

(Report of Northumbria OUGS Excursion, June 2014)

Paul F. V. Williams

Introduction

During several earlier field research visits to Arran we had many times gazed at the remarkable sight of Ailsa Craig sitting (or hovering) in the Firth of Clyde as we gazed on it from afar. The opportunity to go and examine this interesting volcanic plug was thus tempting, and when the possibility arose as a preliminary to the branch visit to the Ballantrae Ophiolite it was eagerly grasped. An excited group gathered on the quayside in early June, to fulfil this aim. Surprisingly, despite it being a beautiful day in early summer, with hot sunshine, wall-to-wall blue sky, and no wind, we were assured by the boatman that there was a strong northerly blowing, and that we'd not be able to get up to the jetty to disembark, and thus our visit to Ailsa was off.

Byne Hill

Undeterred, although disappointed, we decided to go up a hill instead; there was one very conveniently near by, Byne Hill. This was a real treat, and helped to make up for our loss of a sea voyage. Along the approach track there were some massive boulder conglomerates, then a small cutting in dark igneous rocks, then a trackside quarry in some very greenish-coloured rocks. The Cyprus veterans in the trip instantly recognised these as serpentinites, although they were dissected by numerous tectonic lineations, and certainly not as massive as those seen earlier in the year in the Mediterranean. As we began our climb to the top, we passed some small outcrops of what looked like gabbro. White translucent laths of plagioclase and small brown-black stumpy crystals of pyroxene confirmed this. As we climbed higher we spread out across the hillside so as not to miss any outcrops that appeared. Very soon people were registering more igneous rocks, not so coarse-grained, and definitely not gabbro. These were grey crystalline rocks, still with plagioclase, but far less ferromagnesian minerals than the gabbro below, and were dioritic in character. As we progressed higher up the hill the weathering character of the rocks changed, becoming more rounded and widely jointed, and much lighter in colour. These highest units contained quartz and plagioclase, with biotite mica as the main ferromagnesian component, and were identified as tonalites. Indeed some of the material sampled was light enough in colour to be called leucotonalite, or Trondhjemite (Fig. 1).

The field evidence began to hint at the possibility of an ophiolite, a section of originally oceanic lithosphere. Given the associated serpentinite, also characteristic of ophiolites, the igneous rocks of Byne Hill could be interpreted as plagiogranites. What we were looking at here was a late-stage differentiate of mafic, basaltic magma into more felsic components, which classically are found within the plutonic intrusive rocks of ophiolites. Here at Byne Hill a succession of more felsic components derived from the gabbro had been produced, progressing through diorite to the core of leucotonalite. What we weren't able to observe due to poor exposure at the contact was that the gabbro was also chilled against the serpentinite, indicating that gabbroic magmas had been *intruded* into structurally lower ophiolite units. If this was indeed an ophiolite that we were looking at, it meant that gabbroic magmas were still being generated during the early stages of tectonic disruption, i.e. of obduction, to account for the juxtapositional relationship between the two rock types. This posed interesting questions about the relative timing of intrusive and structural events.

It had been a super summer day, and our disappointment from earlier was consigned to distant memory. We celebrated in style in the Harbourhead Restaurant in Girvan with some excellent cuisine, fine beverage and good company (Fig. 2).

Craighead Quarry

Some of the party were camping over this weekend, and the opportunity to visit Craighead Quarry on Saturday morning en route from the campsite before reaching the first locality was not to be missed. This, however, turned out to have mixed blessings. For a start, this SSSI site was very overgrown and access proved tricky.

Figure 1 Trondhjemites near the summit of Byne Hill.

Figure 2 Convivial group in the Harbourhead Restaurant, Girvan.

© OUGS ISSN 2058-5209

Figure 3 Pillow lavas, Balcreuchan Beach.

This was not helped by the beehives, the occupants of which, on hearing us arriving came out to protect their hives, resulting in two senior members of the branch committee being rendered *hors de combat* even before the first locality! But with true pioneering spirit a way in was found, and a rich Ordovician marine shelf fauna of corals, brachiopods and bivalves was the reward.

Balcreuchan Bay

Smarting (stinging?) from this encounter, we reached the first scheduled locality of the day at Balcreuchan Bay. After the exciting scramble down to the beach we were treated to a feast of geological delights: pillow lavas in abundance and some serpentinites on the beach, too (Fig. 3). These very recognisable serpentinites were in tectonic contact with black, basaltic lavas, and with their pillow structure, had obviously been erupted under water (Fig. 4). The serpentinites were a crucial piece of evidence favouring the ophiolite origins of the rocks exposed here. Serpentinites form through the interaction of water with the ferromagnesian minerals olivine and pyroxene, and thus their presence is indicative of former mafic, or more generally ultramafic parents. For ophiolites, serpentinites thus record the former presence of mantle (harzburgite) or lowest crustal (dunite) lithologies.

South of the bay, some lovely volcanic pillow-breccias were also exposed, clast composition dominated by fragmented pillows. This reinforced the submarine eruption inference. Along the beach and back wall of the bay there were more well-developed pillow lavas, but below a major N–S trending fault displayed to the north end of the bay, there were also less pillowed sheet flows. Although these sheet-flow lavas also *looked* like basalts, some of them were in fact quite chemically distinct.

Figure 4 Balcreuchan Bay, showing tectonic contacts between ordinary island arc submarine basalts (upper left), boninite lava flows (lower left), and serpentinites (right fore-ground).

We learned that these different ones were a unique rock, called 'boninite'; we were looking at the first unequivocal boninites in the British Isles, and currently the *only* ones! Boninites are *basaltic*, but are enriched in Mg and Cr, and have comparatively high water content; they are also enriched in the LILE elements Rb and Sr, and, importantly, are geochemically distinct from MORB lavas.

The pillows could simply represent submarine basaltic lava flows generated in any number of settings, but the boninite flows are something quite different. Boninites were first recognised (eg Cameron *et al.* 1979) and described from the Izu-Bonin-Mariana arc system in the western Pacific, where boninite lavas occur in a fore-arc extensional basin above a subduction zone. Hence a subduction setting was suggested for the boninites found here at Balcreuchan Bay. And the Island Arc geochemical signatures found for the *pillowed* lavas would also fit with this interpretation, being part of the classic arc inventory. Geochemical investigation of the plutonic igneous rock of the Byne Hill locality also indicated an extensional supra-subduction zone setting.

Figure 5 Tectonic contact, radiolarian chert and volcano-sedimentary lava breccia, Bennane Lea (shaft of hammer roughly aligned with chert bedding).

Bennane Lea

A few kilometres south, the coastal and beach section at Bennane Lea on the south side of Bennane Head was the next objective. Easily identifiable serpentinites are splendidly exposed along the beach at Bennane Lea, along with volcano-sedimentary units of pillow-breccia; but farther north layered rocks came into view. These were very hard and splintery, showed a conchoidal fractures, and were bedded on a scale of *c.* 100mm units. Again, Cyprus veterans were able to identify these layered rocks as bedded cherts — radiolarian cherts in fact — looking very similar to those seen on the shores of the Mediterranean east of Paphos (Fig. 5). These cherts at Bennane Lea were also characteristically red-brown in colour, but also showed good examples of wet sediment slump folds (Fig. 6). And with the serpentinites, cherts and pillow lavas now recognised, all the components of the Steinman Trinity were in place. This would now definitely fit with an ophiolite interpretation. Here, however, the cherts were strongly folded, and were seen to be in tectonic contact with the serpentinised harzburgites and dunites. And the volcano-sedimentary breccias were also in tectonic contact with the serpentinites. It was becoming more apparent that this ophiolite had been obducted, and tectonically dismembered, as we had serpentinites of mantle origin juxtaposed against cherts of sea-floor origin. Further, as at the previous locality, this juxtapositional relationship was also observed, with boninite lava flows of sea-floor origin alongside mantle serpentinites, separated by major faults.

Figure 6 Slump folds in radiolarian cherts, Bennane Lea.

Figure 7 Contact between pegmatitic gabbro (right of hammer; Bonney's Dyke) and serpentinised harzburgite (left of hammer), Slockenray coast section.

Bonney's Dyke

Farther north along the Slockenray coast more geological delights awaited the party. A sinuous mass of white-looking gabbro, 3–4m wide and *c.* 10–15m long known as Bonney's Dyke, showed spectacular pegmatitic development of pyroxene, and plagioclase, the latter now altered to secondary prehnite and pectolite. Here some of the phenocrysts reached *c.* 50mm in length. At this locality we observed that the gabbro was contact with serpentinites, although we saw no chilling of the gabbro margins in the contact zone (Fig. 7). If this was an ophiolite then this gabbro would represent crystallising magmas from a high-level magma chamber, consistent with the occurrence of plutonic intrusives at intermediate depths within a typical ophiolitic succession, and characteristic of Penrose-type oceanic crustal architecture. But the absence of chilling suggested that this gabbro had been *intruded into the mantle harzburgites while they were still hot* (Fig. 8)! This suggests that mafic magmas were still available for intrusion while uplift and obduction of the mantle units was taking place. This presents another intriguing situation for the timing of ophiolite generation and the timing of subsequent obduction and dismembering.

The beach around Bonney's Dyke also showed some superb examples of pyroxenite veins intruding the mantle harzburgites, with the pyroxene serpentinised and altered to bastite, in 50–100mm sized crystals (Fig. 9, *opposite*). This is again another well-documented feature of ophiolites, where pyroxene-rich melts generated from the mantle harzburgite can be intruded back into the upper parts of the mantle.

Farther along the beach section exposures of lavas in contact with the serpentinites showed evidence of pervasive Ca-metasomatism as development of white veins and inclusions of prehnite and pectolite. This was rodingite, named from the Roding River in the Dun Mountain ophiolite complex of South Island New Zealand (also the type-locality for dunite (von Hochstetter 1859) (Fig. 10, *opposite*). This Ca-rich, low-temperature alteration is often associated with the process of serpentinisation, and is found in many of the world's ophiolite bodies.

Figure 8 Gabbro pegmatite, Bonney's Dyke, Slockenray Coast: plutonic intrusive unit of ophiolitic succession.

Northwards along the shore from Bonny's Dyke we saw exposures of polygenetic conglomerate. These contained large 200–300mm clasts of basalt lava, pillows and seprentinite, plus smaller-sized clasts of chert and shale. This was the Pinbain olistostrome, and was here seen in tectonic contact with serpentinites; and also with volcano-sedimentary units (Fig. 11, *page 84*). It is regarded as oceanic crustal material of both volcanic and sedimentary origin, incorporated into a subduction trench and later accreted onto the leading edge of the over-riding plate by compressive tectonic forces, in this case associated with obduction.

Figure 9 Pyroxenite vein in serpentinised mantle harzburgite, Slockenray coast section.

Farther along the shore towards Kennedy's Pass we found spectacularly folded beds of grey metapelites and flaggy greywacke units displaying tight folding, belonging to the overlying Barr and Ardmillan Groups, of Llanvirn to Caradoc age (Fig. 12, *overleaf*). We interpreted these strata as the sedimentary cover over the earlier ophiolitic crust, with unconformable contacts developed farther north along the coast, effectively constraining the age of the igneous complex to pre-Llanvirn in age.

This had been another super day with some fantastic but mind-blowing geology, the meaning of which was only just beginning to sink in. Impressed with our previous visit the night before, the group again repaired to the Harbourhead Restaurant for convivial evening sustenance in warm summer sunshine.

Knockdolian Hill

As the Sunday morning sunshine began to dilute, we began our climb part-way up Knockdolian Hill. Underneath the site of Duniewick Hill Fort 12m high exposures on the hillside revealed grey rock units with sub-vertical linear features dissecting the exposed faces into 1–2m bands. The contacts between the bands were denoted by very fine-grained lithologies, while in the middle of the bands grain size was large enough to identify the rock as igneous, and of doleritic composition. This was the final piece of the jigsaw we needed to complete our ophiolite story, and again, Cyprus veterans identified what we beheld. These were dykes, and with so many of them, all in contact, we recognised them as a sheeted dyke complex, the telltale signature of spreading ridge magmatism (Figs 13 and 14, *page 85*).

As the weather began to deteriorate the 'Garden Design and Architecture' sub-group took over, and led an exciting session of pebble collecting on the beach before our final departure.

Figure 10 Rodingite in lavas adjacent to seprentinite, Slockenray coast section.

Figure 11 (left) The Pinbain olistostrome, Pinbain shore section.

Figure 12 (below) Tight folds in Barr and Ardmillan metapelites, Kennedy's Pass.

Figure 13 Sheeted dykes, Knockdolian Hill.

Conclusions

The plutonic igneous and volcanic successions exposed at Ballantrae, along with the associated volcano-sedimentary successions, the radiolarian cherts and olistostromes, as shown on the accompanying geological map, represent structurally dismembered remnants of ophiolitic oceanic crust and deep ocean floor sediment (Fig. 15, *overleaf*). The age range of generally Tremadoc to Arenig for interbedded sediments, and ages of *c.* 470Ma for volcanic and plutonic components places this complex within the early stages of the Caledonian Orogeny.

Broadly, the complex represents the development of a volcanic arc and attendant subduction system within the Iapetus Ocean during a phase of crustal compression that ultimately resulted in closure of the ocean and collision of the arc with the Laurentian continental margins. At some point during arc history spreading ridge magmatism developed in response to local crustal tension driven by slab roll-back or break-off, to generate sections of new oceanic crust, and the formation of a supra-subduction zone ophiolite. Under ongoing convergence and ocean closing this ophiolitic crust was then obducted and accreted onto the Laurentian continental margins during the Grampian phase of the Caledonian Orogenic event at *c.* 470Ma.

But this is rather an oversimplified view of the events that gave rise to the Ballantrae Ophiolitic Complex, because it does not account for the presence of not just SSZ ophiolitic volcanics, but also the similarly abundant extrusive volcanic rocks with within-plate geochemical signatures, and those with arc signatures too. It would appear that more conventional arc volcanics, and

Figure 14 Dyke with chilled margins, Knockdolian Hill.

within-plate volcanics were also being produced in the vicinity, from different igneous centres and in different settings; also that the products from these were at some later stage brought into juxtaposition by the forces of obduction, possibly by significant magnitude strike-slip movement over distances of sometimes tens to hundreds of kilometres lateral displacement.

There are many questions that remain to be answered about the Ballantrae Complex relating to the sequence of events and their timing. However, it nonetheless represents a magnificent example of an igneous and associated sedimentary complex that witnesses and documents a significant series of events in the geological history of Britain as the Iapetus Ocean was closing in the Ordovician. The ensuing continental collision of the arc with the Laurentian margins gave rise to the Grampian phase of the Caledonian Orogeny, and resulted in the building of the Caledonian Mountains and the incorporation of parts of Laurentia into what eventually became northern Britain.

References and other sources

Cameron, W. E., Hisbet, E. G., and Dietrich, V. J. 1979 'Boninites, komatiites and ophiolitic basalts'. *Nature* **280**, 5503

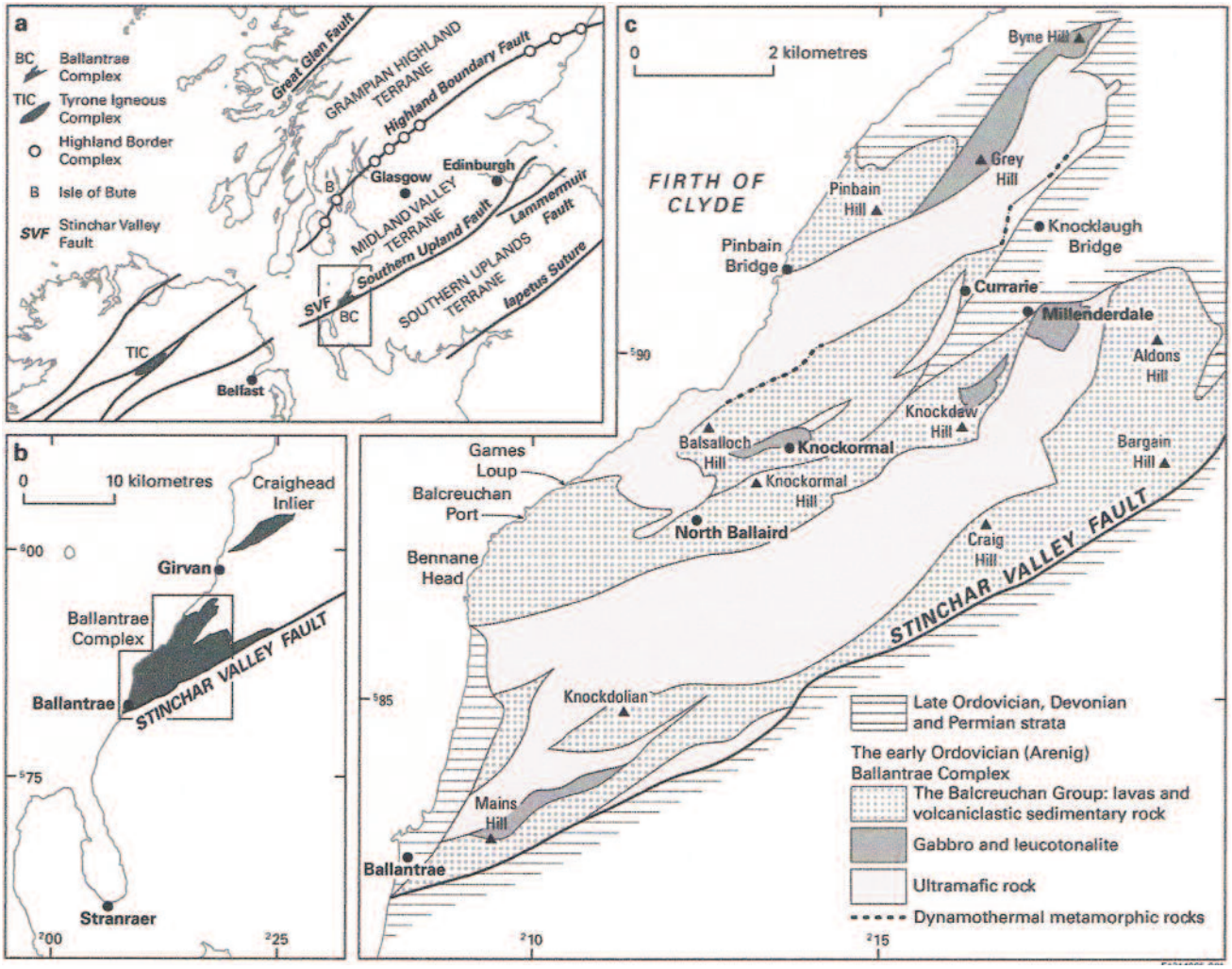
Stone, P. 2014 'A review of geological origins and relationships in the Ballantrae Complex, SW Scotland'. *Scottish J Geol* **50**, 1–25

Oliver, G. J. H., Stone, P., and Bluck, B. J. 2002 'The Ballantrae Complex and Southern Uplands terrane', *in* Trewin, N. H. (ed.) *The Geology of Scotland*. London: Geological Society, 167–200

Stone, P., and Smellie, J. L. 1988 *The Ballantrae Area: a Description of the Solid Geology of Parts of [the] 1:25 000 sheets NX08, 18 and 19*. Classical areas of British Geology. London: HMSO for British Geological Survey

von Hochstetter, Christian Gottlieb Ferdinand Ritter 1859, *cited in* Johnston, M. R. 2007, *19th-Century Observations of the Dun Mountain Ophiolite Belt, Nelson, New Zealand, and Trans-Tasman Correlations*. London: Geol Soc Special Publ **287**, 375–87

Figure 15 Geology of the Ballantrae Ophiolite Complex (after Stone and Smellie 1988).



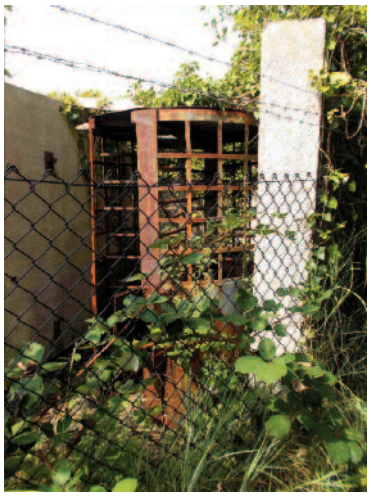
The Severn Crossings

(OUGS Severnside and South West branches field trip, 6 September 2014; led by Dave Green, FGS)

Averil Leaver (text), John de Caux (photographs) and Dave Green (diagrams)

Our two groups (from Severnside and South West branches) made a good-sized audience for Dave Greens's exploration of the two Severn Crossings and the associated geology. A short walk on the English side brought us to the site of the old ferry crossing terminal. There were a few memories recalled of this now abandoned and dilapidated gateway to and from Wales (Fig. 1).

Figure 1 The disused eastern ferry terminal used before the bridges were built.



At the beach we could all pick out the changes in strata as outlined on the stratigraphy diagram (Figs 2, 3 (*overleaf*) and 4 (*page 89*)). The colour changes were very helpful. The red Mercia Mudstone, which derives from a desert environment with few fossils and occasional dinosaur footprints, extends from Dorset to Yorkshire. There are three explanations for their origin:

- wind-blown dust close to a sea;
- a large ephemeral saline lake; or
- occasional rain bringing wadi flows to a central mudstone area.

The controversy continues.

Figure 2 Severnside and South West branches members on Aust beach.

As we walked along the access road to the beach Dave pointed out the Tufa deposited from a stream emerging above the Mercia Mudstone in the cliff. This is the result of $CaCO_3$ being dissolved from the overlying Lilstock Formation limestone (formerly 'White Lias') and then precipitated out again when the water emerged as a spring.

There were several other layers that drew our attention. The Westbury Formation or 'Bone Beds', were sought out by several members, who searched the cliff falls for fossils laid down within this layer. They were hunting for fish bones and teeth among the marine fossils.

The rest of the group became involved in a deep discussion about the formation and sequence of the gypsum and Satin Spar found within the Mercia Mudstone Group at the base of the cliff (Fig. 5, *overleaf*). The gypsum is the result of evaporation in a desert environment, the first mineral precipitated from an ephemeral sea, and Satin Spar is a secondary form of this mineral. The complex veining with intersecting veins and shear structures was a 3D puzzle that provoked much discussion. It certainly got our 'little grey cells' working!

We spent some time looking at the Severn Bridge and relating its position to the geology. This site was chosen as the narrowest point of the estuary (Fig. 6, *overleaf*). The engineers then made use of the exposures of Carboniferous Limestone for the east tower and anchor point. On the west side the tower had to have deep foundations to penetrate the Mercia Mudstone and find anchorage on the Carboniferous Mudstone below the unconformity. The west anchorage was also much deeper, to reach the Carboniferous Limestones (Fig. 7, *page 90*).

After a pleasant lunch in the shadow of the western pier (Fig. 8, *page 90*) we walked towards Beachley Point to a place where the low cliff stepped out. Here, hidden by the shrubby growth Dave revealed a reverse fault (Fig. 9, *page 90*), which brought the Carboniferous Limestone and 'Dolomitic Conglomerate' up against the Mercia Mudstone. We were able to identify fault breccia and slickensides. *(text continues on page 90)*

© OUGS ISSN 2058-5209

Figure 3 (above) Aust cliff. (Figure 4 is opposite.)

Figure 5 (inset) Gypsum intrusions at base of Aust cliff.

Figure 6 Geological Map of the Severn Bridge.

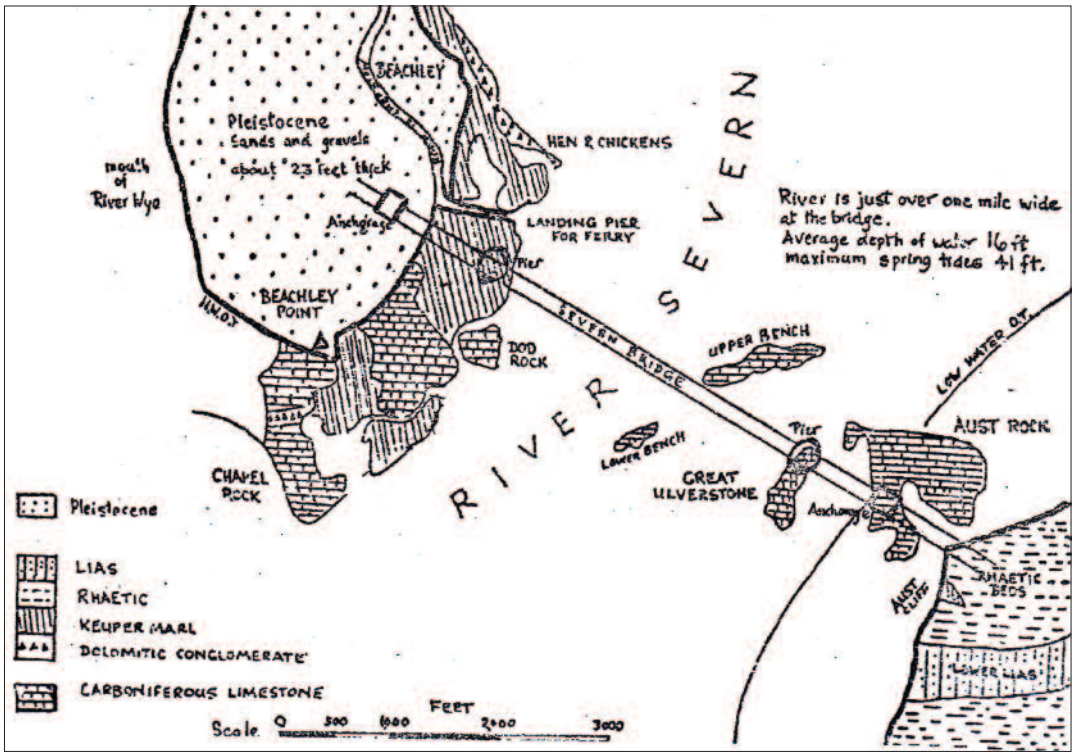
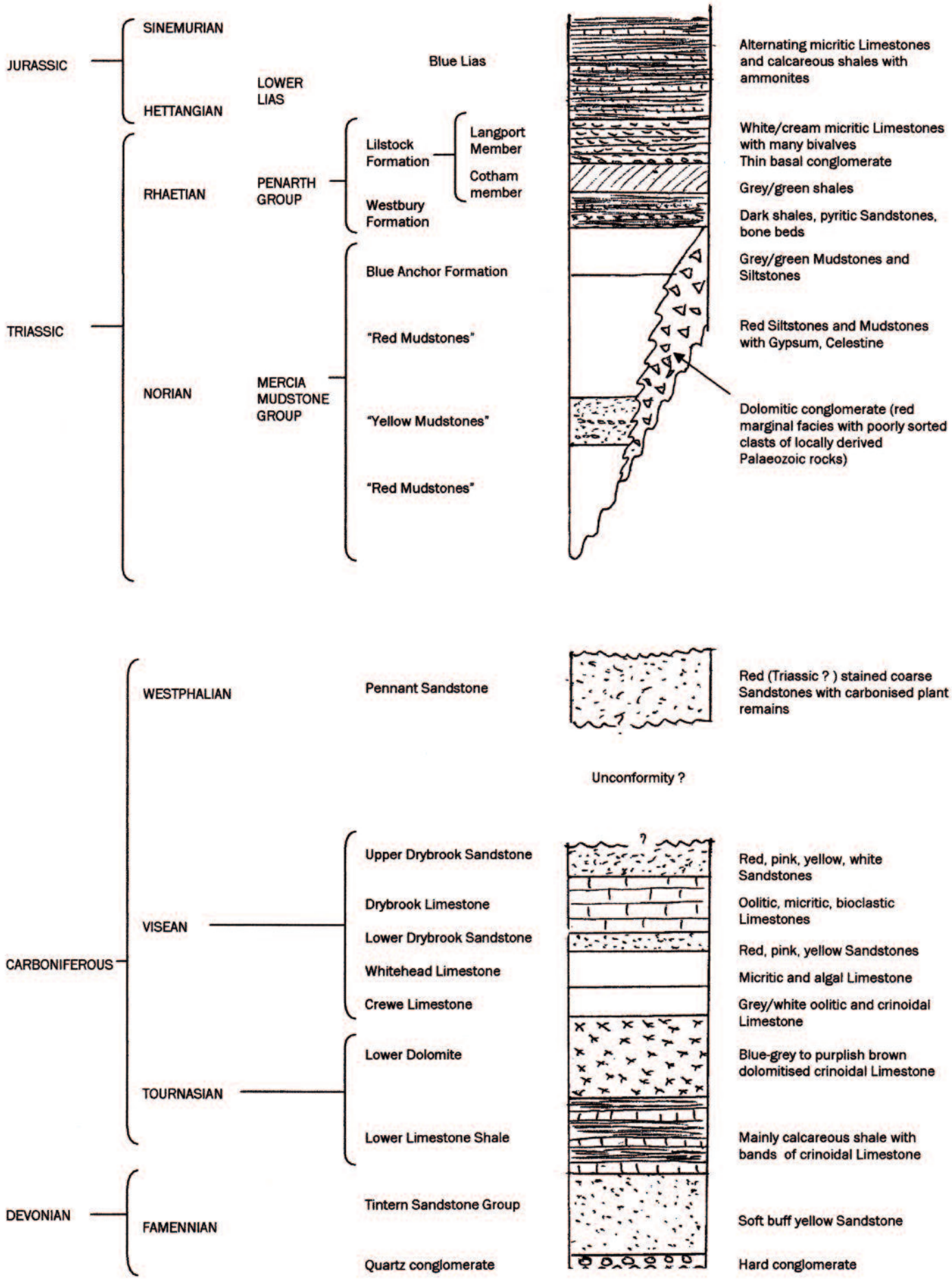


Figure 4 Stratigraphic log of the Chepstow area.



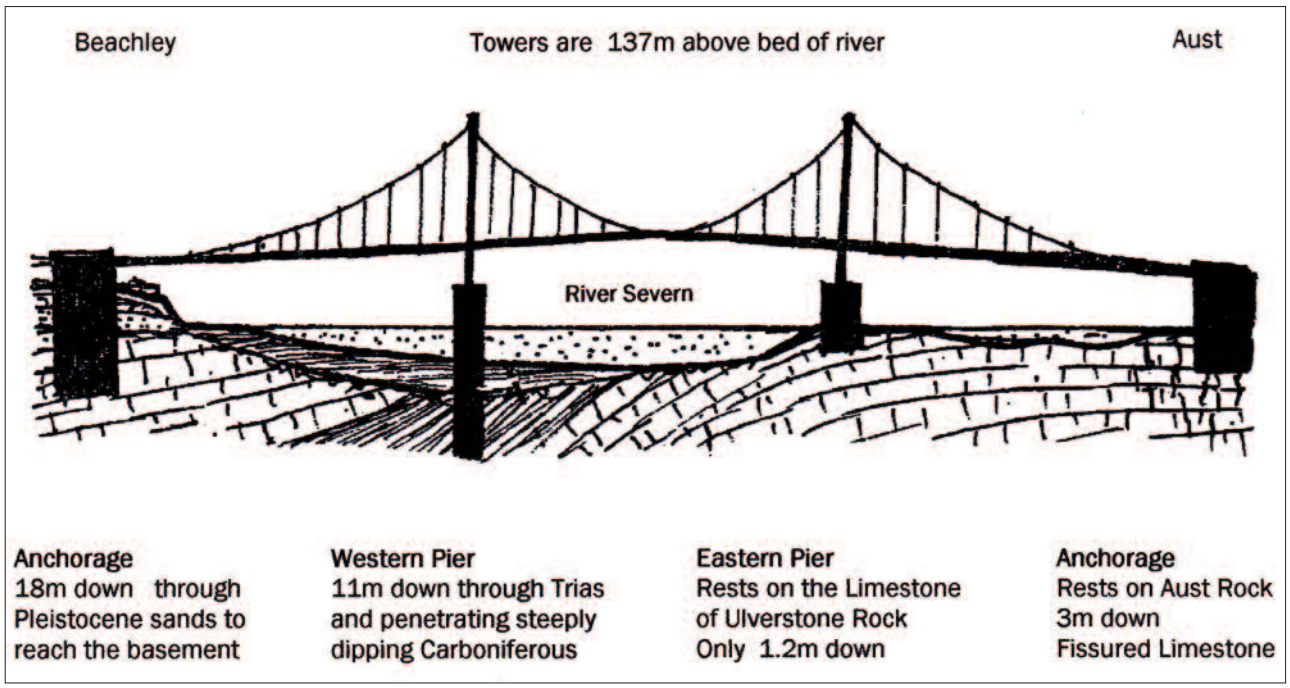


Figure 7 Engineering Geology of the Severn Bridge.

Figure 8 The western pier of the first Severn Bridge.

Figure 9 Reverse fault at Beachley.

(continued from page 87)

Dave's sharp eyes picked out some 'Bristol Diamonds' (Fig. 10), quartz geodes formed where anhydrite nodules had been replaced by quartz. In Victorian times these geodes became a synonym for something 'bright but worthless'.

Around the corner we stood on the dome representing the nose of a south-plunging fold in Carboniferous Limestone. Dave pointed out how the dip varied around the dome. This is the N–S trending Beachley-Clanna Pericline, a Variscan fold associated with movements on the Malvern 'axis'. Beyond the dome we could identify more of the conglomerate and pick out the shape of a small wadi valley cut into the Limestone. The conglomerate was actually a breccia, as the clasts were angular, not having been moved far from the source rock, the Carboniferous Limestone. Matrix support suggested rapid deposition from a flash flood.

A short drive brought us to Portskewett, where we walked out to Black Rock on the estuary. Here the river cliff has exposed the Upper Triassic, but a lower sequence than at Aust (Fig. 11). The

Figure 10 A 'Bristol Diamond', cut in two.

Figure 11 The cliff at Portskewett.

changes in texture and colour with a noticeable lack of structures led to a lively discussion on the origin of the rocks. We discussed the diagenetic changes that could have led to colour change in the permeable coarser sandstone, the changes in energy indicated by the mudstones and sandstone grain size, the lack of fossils, but the indication of bioturbation. Dave could not offer any satisfactory answers, as this strata has not been investigated thoroughly — an opening for further study! Turning around we then observed the Second Severn Crossing (Fig. 12), which is actually the third.

Figure 12 View of the Second Severn Crossing from Portskewett.

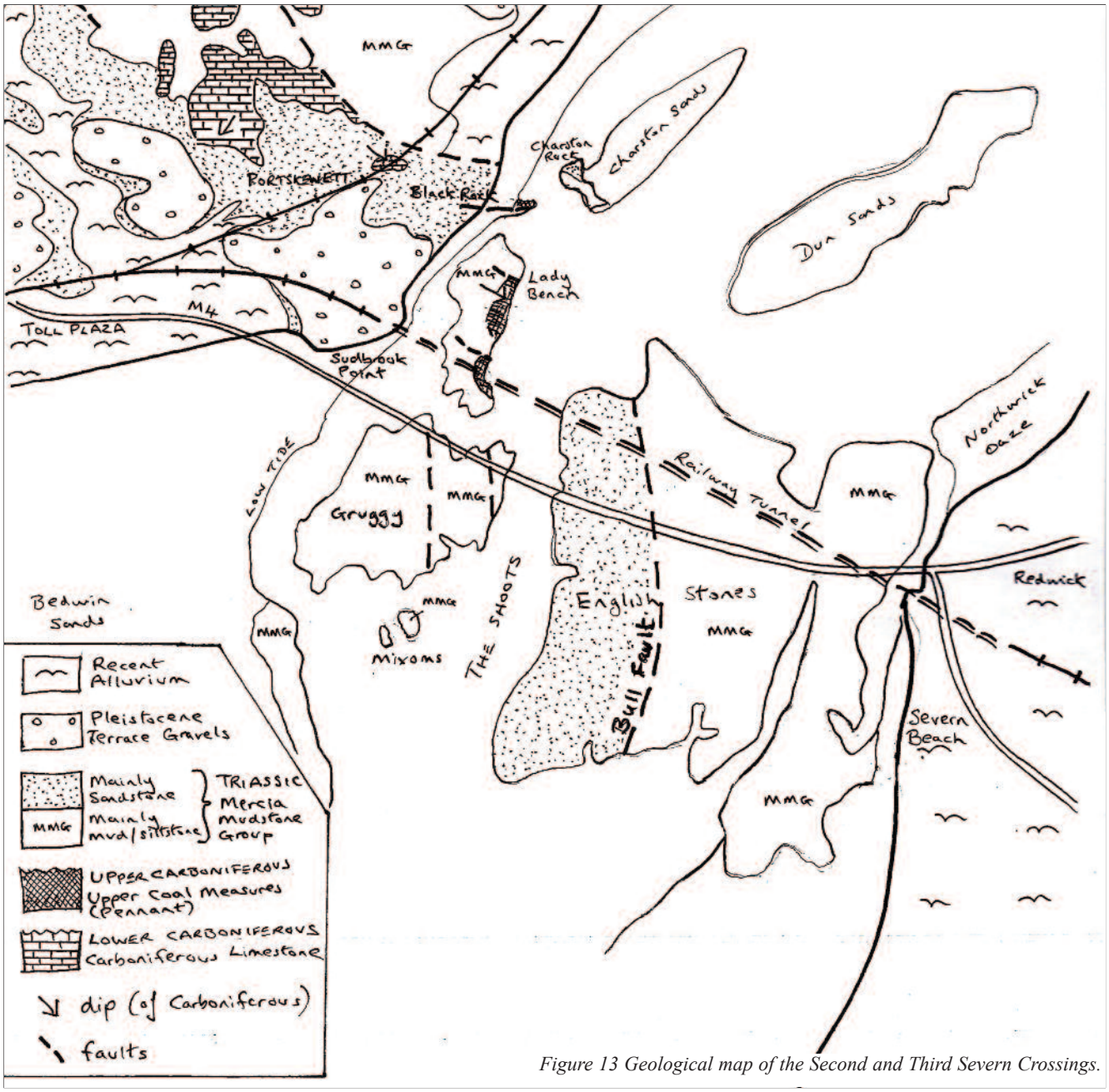
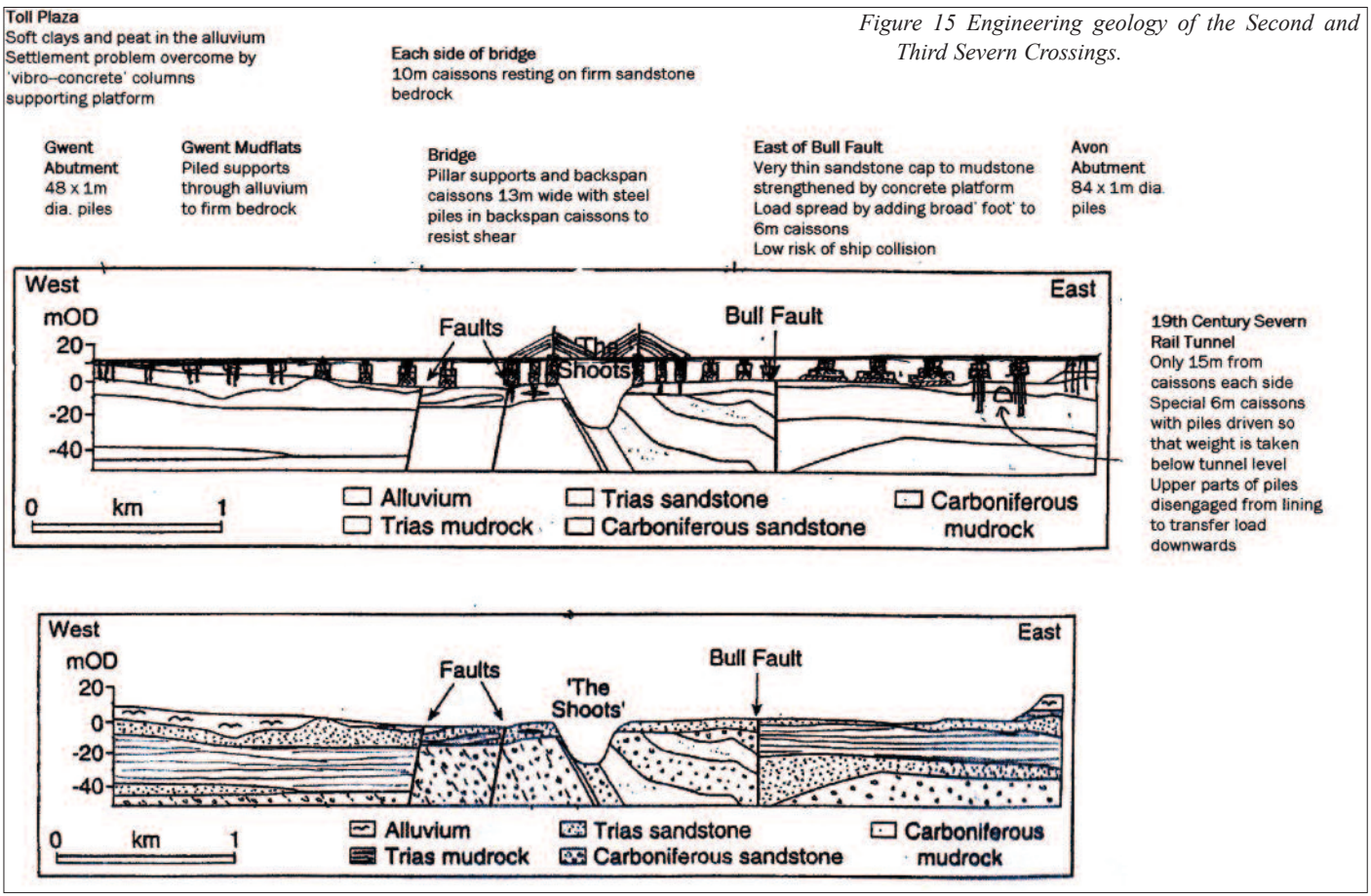


Figure 13 Geological map of the Second and Third Severn Crossings.

Figure 15 Engineering geology of the Second and Third Severn Crossings.



As can be seen from the map of Figure 13 (*opposite*), the Severn Tunnel carrying the railway (Fig. 14, *this page*) passes under the estuary at this point. This tunnel was constructed between 1873 and 1886, its completion delayed by the intersection of the tunnel with a freshwater spring. The consequent flooding necessitated the installation of a large pumping system, which has supplied water to a variety of industries over the century. As can be seen on the diagrams in Figure 15 (*previous page*), the design of the new bridge accommodated the tunnel structure and used the changes in geology to best advantage. The majority of the bridge is built on relatively short caissons supported on flat-lying Mercia Mudstone, which is exposed at low tide. The largest span across the deep-water channel of the Shoots required a cable stay bridge to enable large vessels to pass through to the Sharpness Canal. The toll plaza on the west side was constructed on the peat beds of the Newport Levels and required construction of a special concrete platform to float on the peat. Figure 16 (*overleaf*) is a diagrammatic representation and interpretation of the geology through which the Severn Rail Tunnel passes.

All who attended this day were grateful to Dave Green for the way he helped us interpret the sites we had explored and encouraged us to question what we saw and explore different interpretations in a constructive manner.

Acknowledgements

Figures 6 and 7 are taken from William Dreghorn 1967 *Geology Explained in the Severn Vale and Cotswolds*. Newton Abbot: David & Charles

Figure 14 is modified from information supplied by John Laing — contractors for the Second Severn Crossing (Kitchener, J. N., and Ellison, S. J. 1997 'Second Severn Crossing — design and construction of the foundations'. *Proc Instit Civil Engineers*, 22–34).

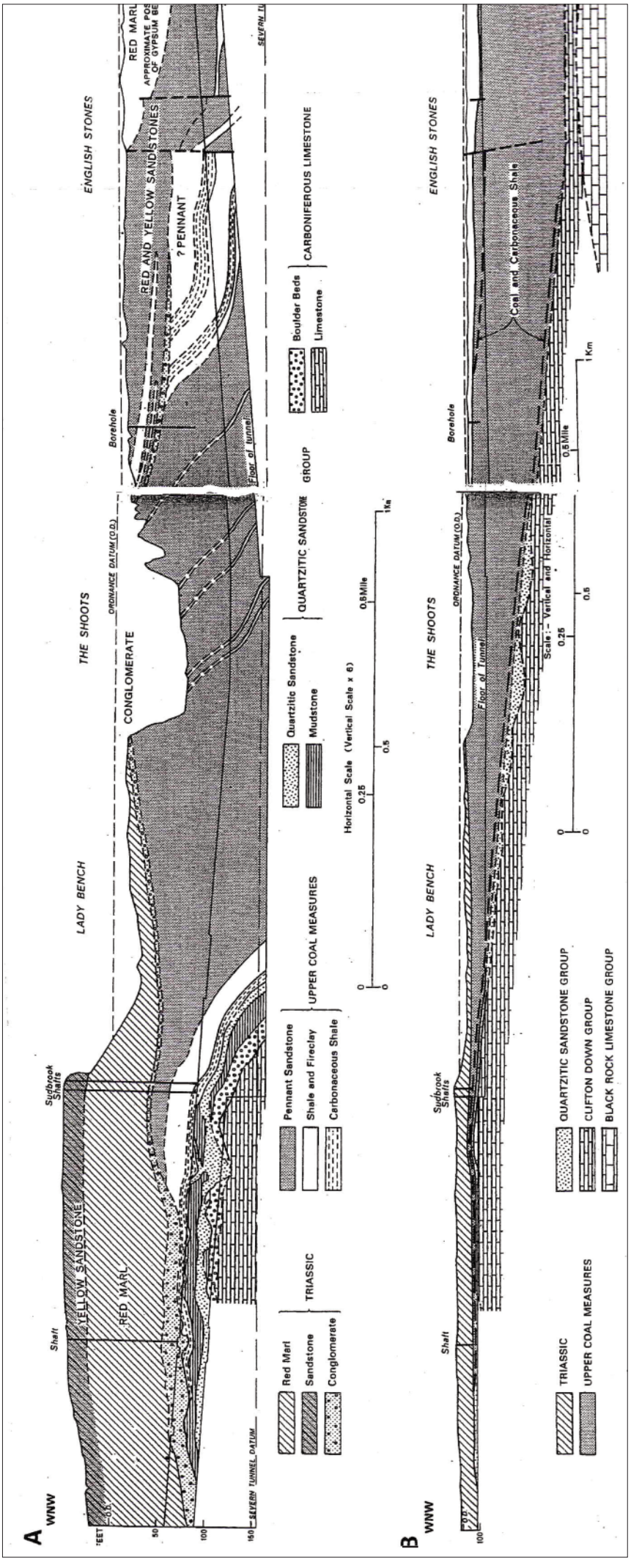
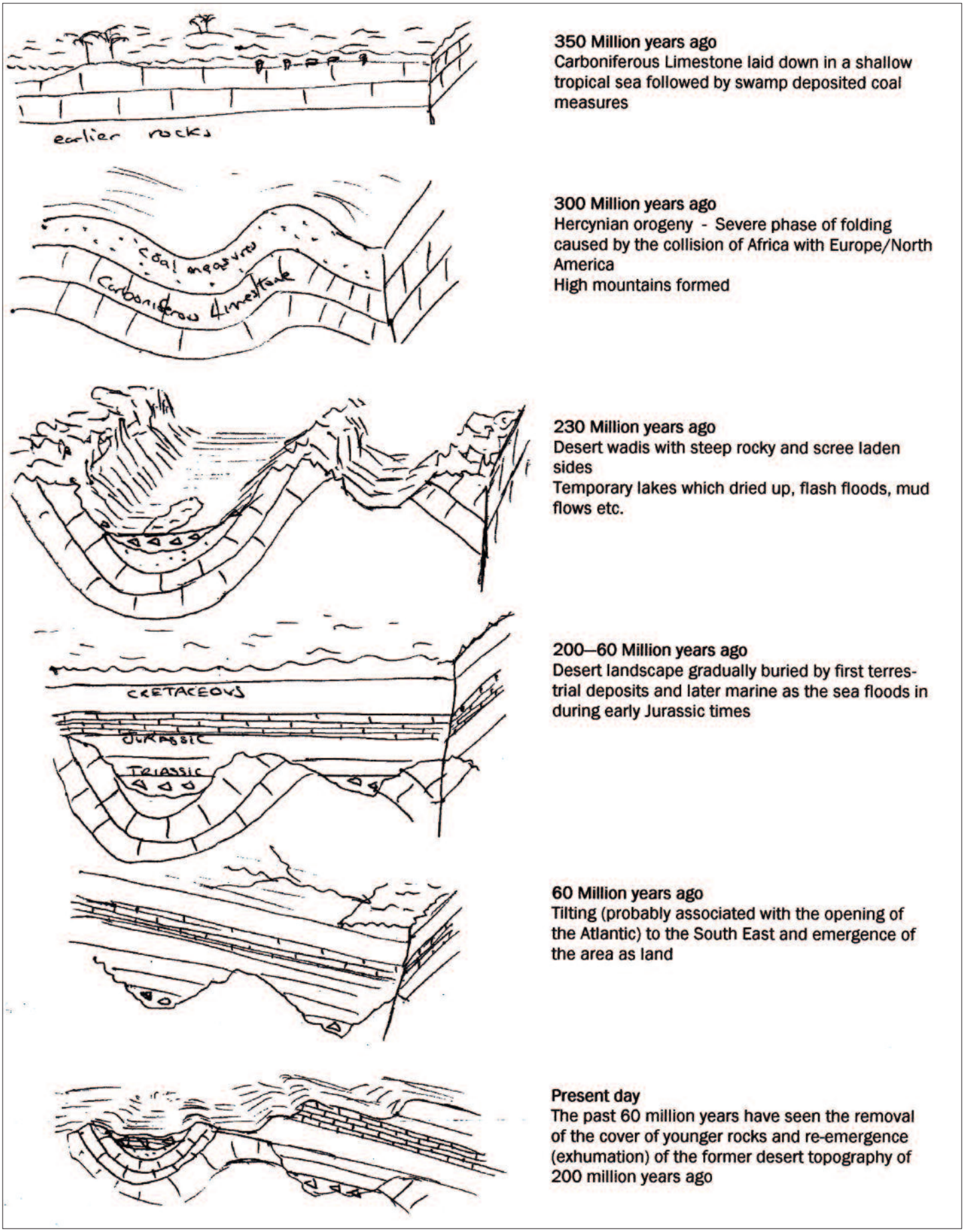


Figure 14 Horizontal section through the western part of the Severn Rail Tunnel.

Figure 16 The exhumed topography of the Bristol–Gloucester Area.


earlier rocks
Coal measures
Carboniferous Limestone
CRETACEOUS
JURASSIC
TRIASSIC
350 Million years ago
Carboniferous Limestone laid down in a shallow tropical sea followed by swamp deposited coal measures
300 Million years ago
Hercynian orogeny - Severe phase of folding caused by the collision of Africa with Europe/North America
High mountains formed
230 Million years ago
Desert wadis with steep rocky and scree laden sides
Temporary lakes which dried up, flash floods, mud flows etc.
200–60 Million years ago
Desert landscape gradually buried by first terrestrial deposits and later marine as the sea floods in during early Jurassic times
60 Million years ago
Tilting (probably associated with the opening of the Atlantic) to the South East and emergence of the area as land
Present day
The past 60 million years have seen the removal of the cover of younger rocks and re-emergence (exhumation) of the former desert topography of 200 million years ago

The dimension stones of Dundrum Town Centre

(Dundrum, Dublin 16, 23 March 2014; led by Susan Pyne)

Isabel O'Brien

Early on Sunday morning, 23 March some members of the OUGS Ireland Branch met on the ground level of Dundrum Town Centre outside the M&S store. It was important to beat the crowds in order to enjoy unobstructed views of the floor slabs — or maybe it was rather to leave unobstructed areas to the shoppers, who would probably be more welcomed by the shopping centre's management than curious geologists.

Dundrum Town Centre showcases all three types of rocks — igneous, metamorphic and sedimentary — in the form of 'dimension stones', which refers to the natural stone that has been quarried and selected, for the purpose of obtaining blocks or slabs with certain specifications as to size (i.e. width, length and thickness) and shape, for use as a building and/or decorative material. The most common varieties of rock used as dimension stone are granite, tuff, marble, slate, quartzite, limestone, sandstone and travertine. The main requirements for a dimension stone are its durability and strength (i.e. mineral composition, hardness and weatherability for outdoor use), as well as colour, grain texture, pattern and the polishing finish the stone can take. When the dimension stone is processed this way, the features showing within the rock can be outstanding. And this is, of course, the reason for our walking tour to Dundrum Town Centre, where the main rock types used as dimension stones — granite, marble and limestone — have been combined, for indoor use, in different colours and shapes to great effect and appearance, creating the beautiful floorings throughout the shopping centre (Fig. 1).

From Susan Pyne's handout notes, the flooring in Dundrum Town Centre was provided and installed by Stone Cladding International. Table 1 shows the commercial names given to stones that were used for all floors. Adjacent to the shopping centre is the Dundrum cinema building, and though not visited during the trip, the stones used there are included on this table as well.

Figure 1 Dundrum Town Centre dimension stones on ground floor — pattern composed of granite, gneiss and limestone.

Table 1 List of commercial names given to the stones used in Dundrum Town Centre

Granite

Amerelo Coto	Blue Orissa	Carioca Gold	Cinza Rajado*	Colibri
Giallo Bras	Hymalaian Blue	Nero Assoluto*	Nero Impala	Princesa**
Rosso Tigrato	Samba White	Shivakashi	Verde Savana**	

Marble (Serpentinite)

Limestone

Verde Olympia	Jura Blue Grey	Jura Red Brown	Jura Yellow	Eastern Cream**

* This stone has been used **only** in the shopping centre.

** This stone has been used i**n both** the shopping centre and the cinema building.

© OUGS ISSN 2058-5209

Figures 2 to 20 show ‘sample’ views of each of the polished rocks.

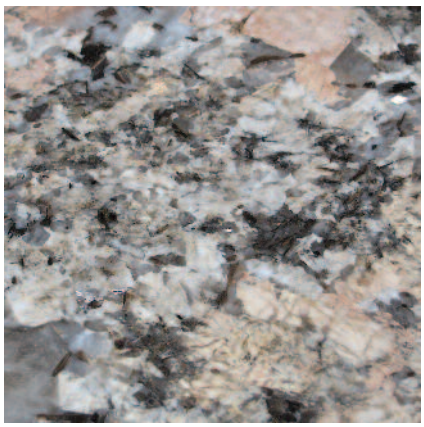


Figure 2 Amerelo Coto granite.

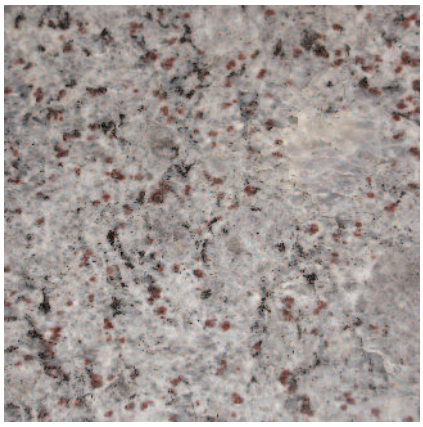


Figure 3 Blue Orissa granite.

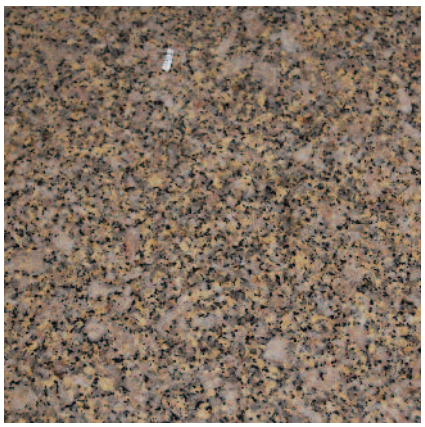


Figure 4 Carioca Gold granite.

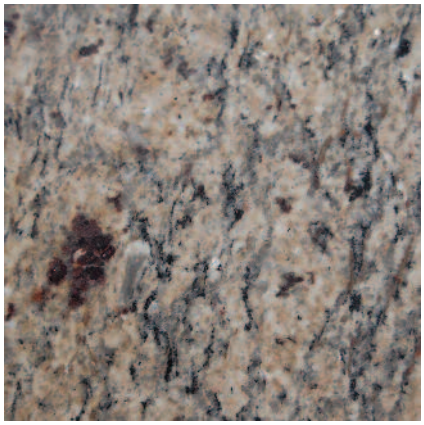


Figure 5 Cinza Rajado granite (polished).

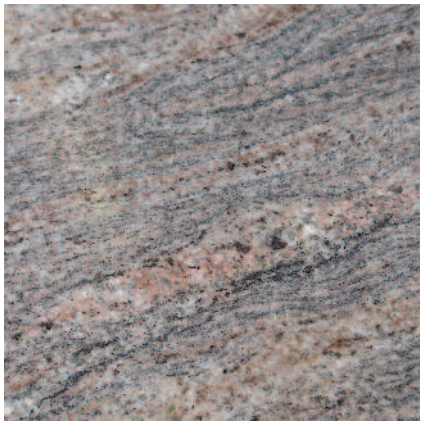


Figure 6 Colibri granite.

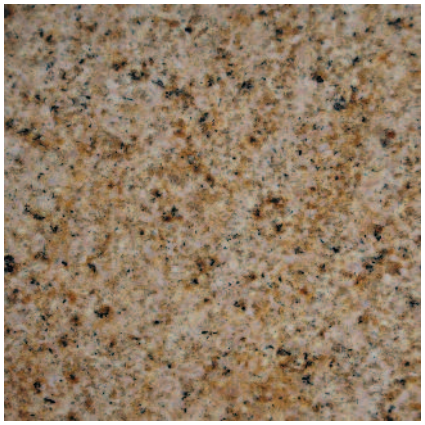


Figure 7 Giallo Bras granite.

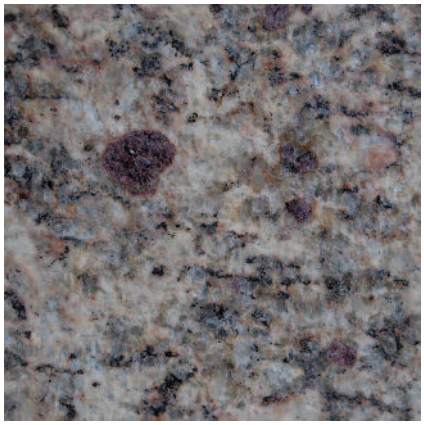


Figure 8 Cinza Rajado granite (unpolished).

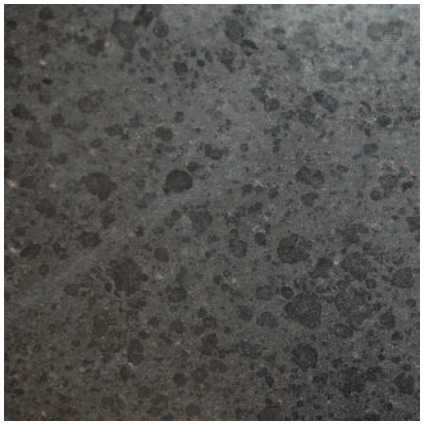


Figure 9 Nero Assoluto granite (weathered 11 years).

Figure 10 Nero Impala granite.

Figure 11 Princesa granite.

Figure 12 Rosso Tigrato granite.

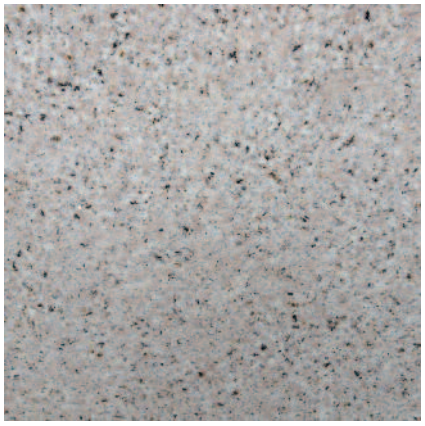


Figure 13 Samba White granite.

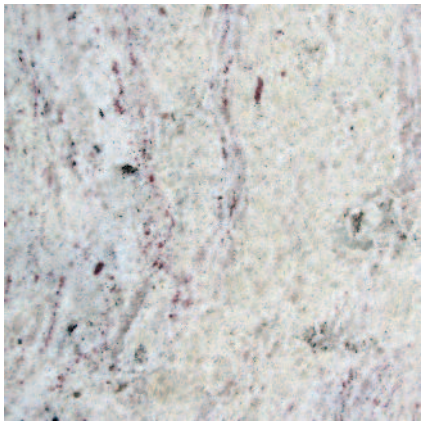


Figure 14 Shivakashi granite.

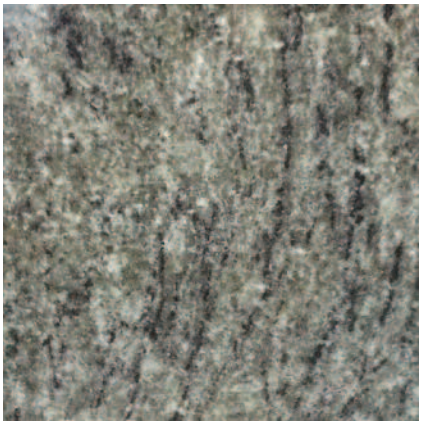


Figure 15 Verde Savana granite.

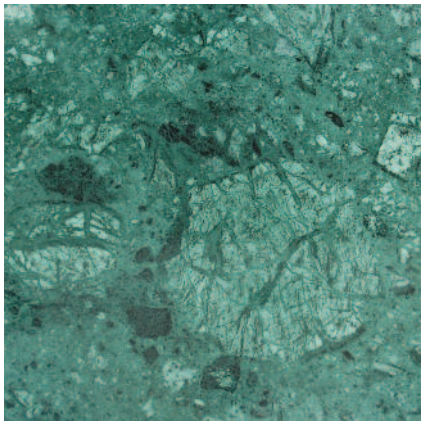


Figure 16 Verde Olympia marble.

Figure 17 Eastern Cream limestone.

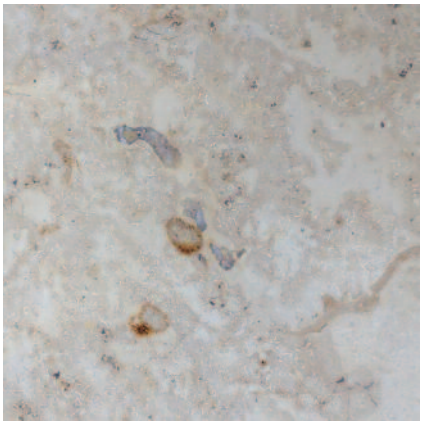


Figure 18 Jura Blue Grey limestone.

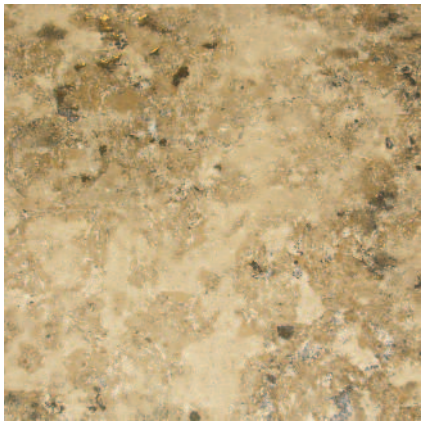


Figure 19 Jura Red Brown limestone.

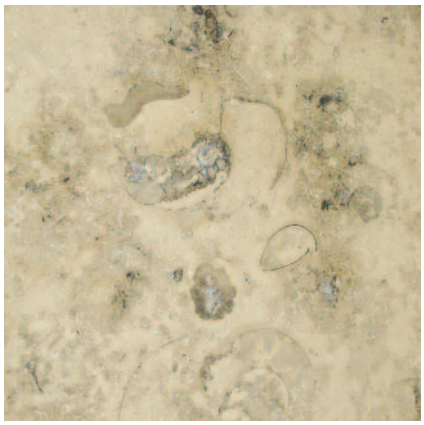
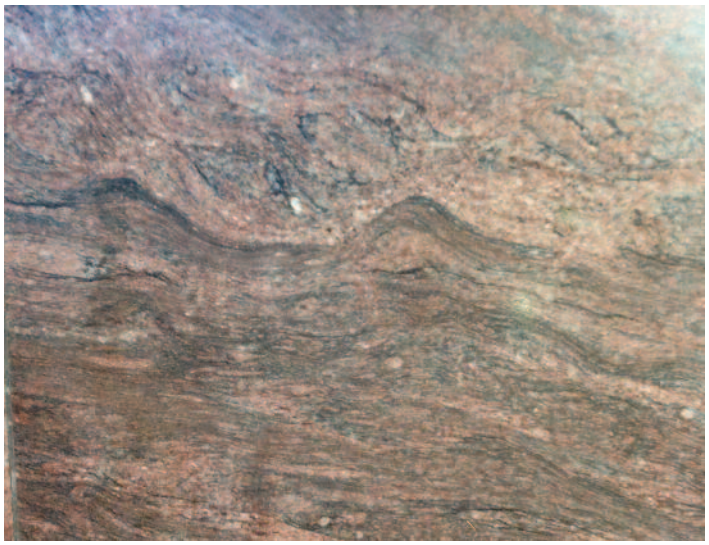


Figure 20 Jura Yellow limestone.

Susan pointed out in her handout that commercial companies use the terms 'granite' and 'limestone' differently from the ways that geologists do, usually referring to granite when the decorative stone is hard and granular, and capable of taking a high polish. However, some of the 'granites' listed in Table 1 are in fact gneisses, and while they had an igneous origin, high temperatures and pressures have transformed them to introduce beautiful movement bands in their appearance (Fig. 21). Meanwhile, a geologist would describe the true granites found in Dundrum as plutonic and intermediate intrusions, and classify them according to their mineral content (i.e. mafic, felsic, etc.).

Figure 21 'Movement' in the grains of the Rosso Trigrato granite due to high pressures.



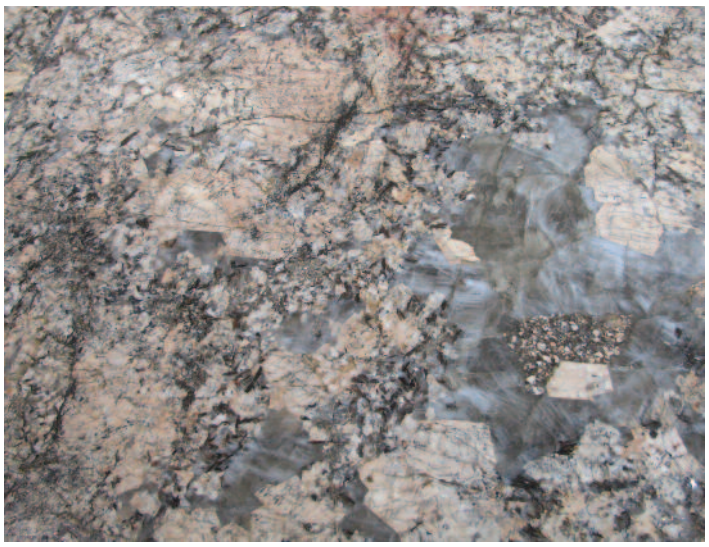


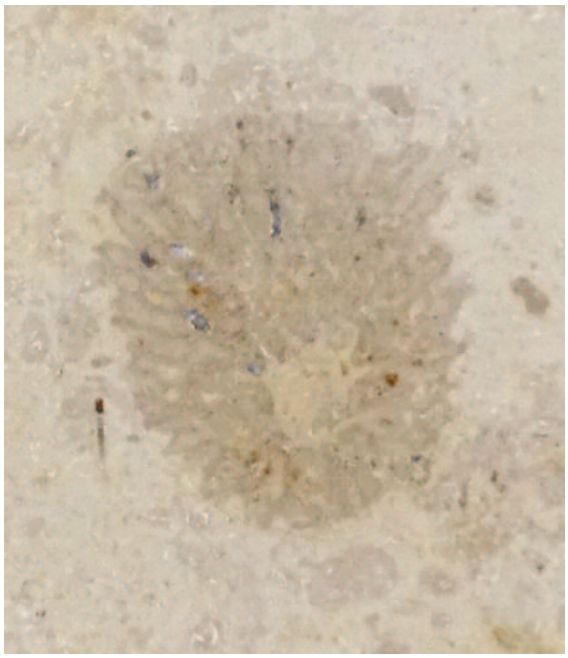
Figure 22 Big crystals found in the Amerelo Coto granite.

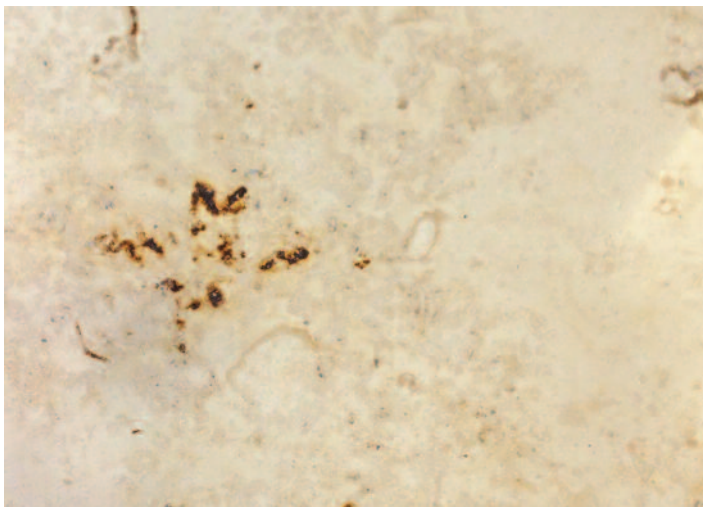
Susan highlighted some interesting features of each of the three rock types that could be appreciated within the different dimension stones. For instance, some granitic pegmatites showed huge crystals with ex-solution textures — intergrowths of quartz and feldspar (Fig. 22).

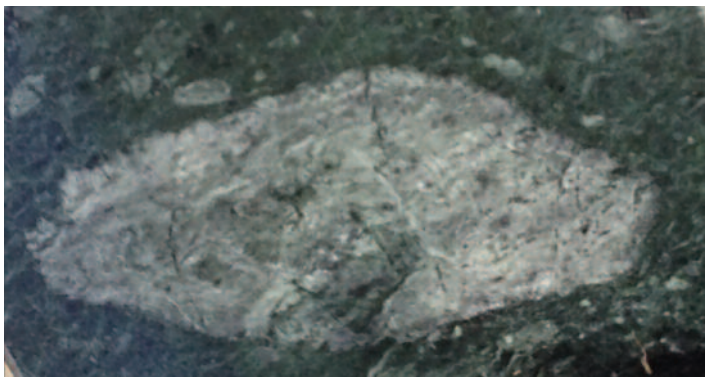
In the limestone slabs, there are beautiful 'pot-pourris' of ammonoids, corals, belemnites and bivalves (Fig. 23). A silvery mineral with mirror-like properties is found everywhere on some of the Jura types of slabs; these are iron oxide crystals, or specular haematites, which are often found in sedimentary rocks. Other Jura slabs just show the rusty runoff colours of the iron oxides.

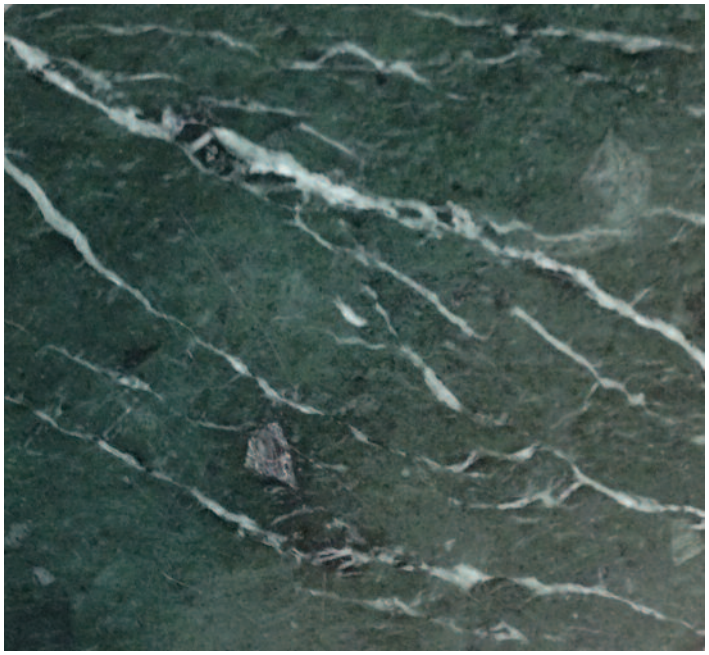
Other noticeable features on the Jura slabs are the different shades of limestone, indicating the conditions in which they formed — for example, the Jura Blue Grey limestone had a muddier, less calm marine environment formation with more-reducing conditions than the other two types.

Figure 23 Beautiful features of the limestone floors in Dundrum Town Centre, showing corals with incrustations of specular haematites, ammonides and iron oxides stains.









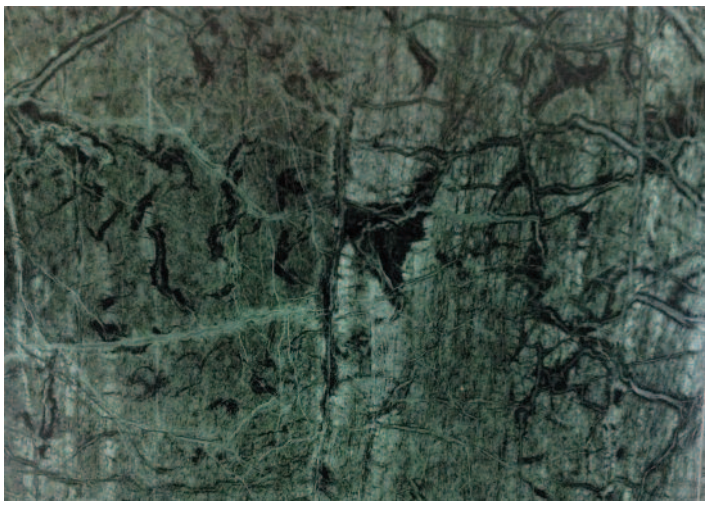


Figure 24 Different features seen in the Verde Olympia marble stones.

Also to be appreciated in the metamorphic rocks, some of the original granites had endured tremendous pressures at depths of 15–20km, to transform into gneiss, lenticular eye-shaped grains of garnet, quartz or feldspar called 'augen'.

Finally, one of the most beautiful dimension stones in Dundrum is the serpentinite rock called Verde Olympia marble (Fig. 24). It has been used to great effect, but in lesser quantities, to break and define the floor spaces.

This rock is composed of one or more serpentine minerals formed by hydrous silicate minerals rich in iron and magnesium. The greenish-blue colour is, therefore, given by the chemical alteration of serpentine due to the metamorphic transformation of peridotite (olivine) from the Earth's deep crust and upper mantle. This green marble, with ghostly quartz insertions, is therefore very different from the marbles with a sedimentary origin.

We slowly rambled to the upper floors, looking to identify all the listed rocks in the handout, while shying away from the most transited areas. Still, some of us enjoyed exploring the floor features on our hand and knees, with the occasional shopper stopping to offer us help to find whatever it was we were looking for. Eventually, a member of the management staff approached us and, with a grin, he asked: "Geologists?" Anyhow, Susan had advised beforehand that they should expect us, and if you plan to take a group of people to Dundrum to admire the dimension stones, it is advisable that you do the same.

The Dundrum Town Centre walking tour ended close to noon, when some of the attendees left while the rest travelled to the National Gallery for lunch.

Thank you, Susan, for organising and leading the tour; it was very interesting and informative, and it has made me appreciate the floors in Dundrum much, much more.

Images and information sources

http://www.stonecladdinginternational.co.uk/materials/ (Accessed 03.07.2014)
http://www.stonecladdinginternational.co.uk/projects/Dundrum-Cinema-Building-37 (Accessed 03.07.2014)
http://www.stonecladdinginternational.co.uk/projects/Dundrum-Shopping-Centre-35/ (Accessed 03.07.2014)
Bonewitz, R. L. (2008), Rocks & Minerals: The Definitive Visual Guide, London, Dorling Kindersley Limited

Acknowledgement

The *POUGS* Editor and the author would like to thank the Dundrum Centre management for accommodating not only the OUGS Ireland Branch visit, but also for their help in allowing Isabel O'Brien to return to the centre to take photographs for this article.

Book review

Benton, Michael J. 2015 *Vertebrate Palaeontology* (4th edn). Oxford: Wiley Blackwell (hardback ISBN 978-1-118-40755-4, paperback ISBN 978-1-40684-7; 480pp; hardback £85.00, paperback £39.93, e-book 31.99)

Michael Benton is Professor of Vertebrate Palaeontology at Bristol University. His research specialises in the macroevolution of vertebrates.

In the preface to the book he lists his five aims in writing the book: (1) to present a readable narrative of the history of vertebrates; (2) to highlight major evolutionary anatomical changes; (3) to show how palaeobiological information is obtained; (4) to survey the present state of discovery of the tree of life for vertebrates; and (5) to highlight career development for aspiring palaeontologists.

The title was first published in 1990. This fourth edition is fully revised and expands on the previous edition, presenting the findings of recent research as well as introducing new topics.

Vertebrate evolution through the Phanerozoic is covered in 11 chapters from 'Vertebrates Originate' in chapter 1 to 'Human Evolution' in chapter 11. All chapters deal thoroughly with a subject or a period of evolution and maintain a clear structure that includes: key questions for the chapter; detailed consideration of many relevant topics; questions for future research; further reading (including useful websites) and a list of references. The book is larger than previous editions and is clearly laid out.

The book contains much from previous editions, as well as new sections that relate to new research or to new topics. Many of the excellent illustrations are kept, and new graphics are included with the discussion of more recent research. Discussion of particular subjects are contained in 72 boxes under three headings: tree of life boxes; exceptional fauna and palaeogeography boxes; and biomechanics and behaviour boxes. Some boxes update the subjects found in previous editions (e.g. relationships of Mesozoic reptiles), while other boxes introduce new subjects (e.g. *Australopithecus sediba*-transitional fossil). In addition there are 29 colour plates. The cladistic framework is strengthened and there is special focus on the new fossil finds in China.

The companion website makes all the figures and illustrations in the text available for downloading for use by students.

This is not a book about the fossils of animals with backbones. Phylogeny, the linking of organisms through a single branching tree, is the basis of palaeontology and is featured throughout. The book is a main textbook for vertebrate palaeontology and aimed at students and anyone with an interest in the evolution of vertebrates. It meets its five aims and is excellent value.

— *Phil Robinson B.Sc.Hons.*

OUGS South West Branch field trip to the Lizard — a fossil ophiolite

Josephine Brown

Introduction

Prof. John Mather and Dr Jenny Bennett led a South West Branch field trip to the Lizard in June 2014. The itinerary was planned specifically to compliment an OUGS Walton Hall Branch field trip in 2007 (Miller 2008).

On the first day we visited Lizard Point to see the Old Lizard Head Series, Man-o-War gneiss and hornblende schist, followed by gneiss and bastite serpentinite at Kennack Sands and Cadgwith for rodingite dykes. On the next day we set out to trace the signature ophiolite rocks on the eastern side of the Lizard Peninsular at Coverack, Godrevy Cove and Porthallow.

An ophiolite sequence is formed at a mid-ocean ridge where the spreading axis stimulates the mantle to rise. Decompression causes the upper mantle to partially melt, forming a magma chamber. Dykes feed basaltic magma up to the sea floor to be extruded as pillow lavas (Fig. 1).

Essentially, gabbro, dolerite and basalt are of similar mineralogy, the main difference being that gabbro is coarse-grained (having taken longer to cool), dolerite medium-grained and basalt fine-grained. Within the magma chamber gabbro crystals form, with ultramafic cumulates including peridotite settling out to sit upon the resultant mantle residue of deformed harzburgite and dunite.

Sometimes, when nearing the end of a subduction tectonic event — such as the Variscan Orogeny — when continent meets continent, an ophiolite can be obducted onto the continental lithosphere. The ophiolite as identified on the Lizard was thought to have been emplaced onto the Laurasian Plate when, during the Devonian, Gondwanaland advanced from the south causing the Armorican Terrane to collide with the Laurasian Plate on closure of the Rheic Ocean.

Coverack Beach

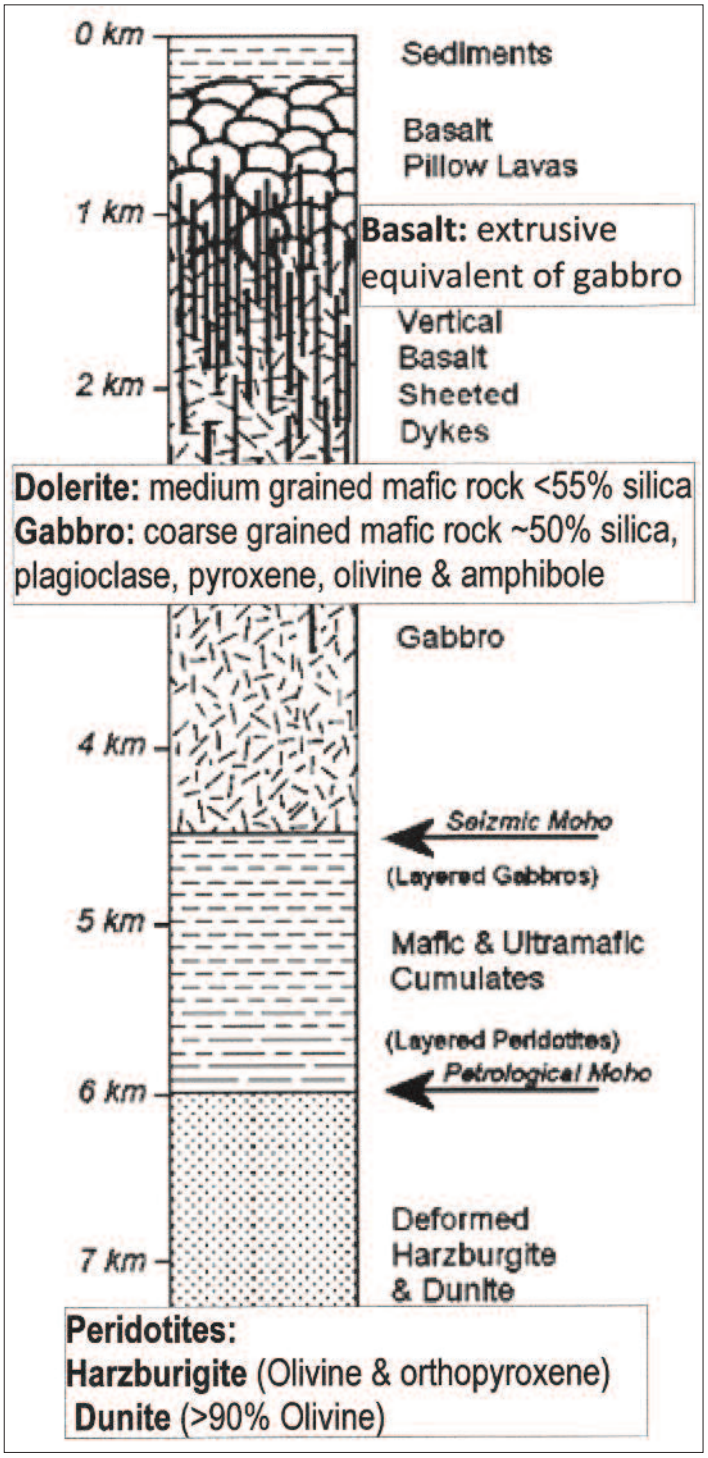
Early geologists had difficulty explaining how Coverack's ultramafic igneous rocks fitted within the context of the high levels of metamorphism seen at Lizard Head. In particular, the Lizard is famous for its serpentinite — a soft, compact, metamorphic rock, the surface of which is commonly referred to as 'lizard skin'. This rock is formed by hydrous alteration of olivine and pyroxene minerals within the ultramafic rocks to form serpentine, a process of known as serpentinisation (Kirk and Cook 1995).

However, it was not until deep-sea drilling facilitated sampling of the ocean crust that an ophiolite could be fully categorised. This enabled Strong in 1975 (cited in Floyd *et al.* 1993) to suggest that the rocks at Coverack represented part of a fossil ophiolite sequence.

We assembled in the car park at the northern end of Coverack Beach, luckily in glorious sunshine completely at odds with the torrential rain being experienced farther inland. The recent winter storms that had caused havoc along the south-west coastline had brought sand into Coverack. Although this made walking along the shore easier, some exposures were harder to find.

Coverack is famous for 'walking across the Moho'. The interpretive board for the general public above the beach states: 'The Moho — or Mohorovičić discontinuity — is named after a Croatian seismologist, Andrija Mohorovičić, who discovered in 1909 that seismic waves changed velocity as they passed through the Earth's crust and into the mantle. The Moho is less deep beneath the ocean, where the crust is formed of heavy gabbro and basalt. Coverack is one of the few places in the world where the ocean crust and the mantle are exposed on the Earth's surface'. As can be seen in Figure 1, there appear to be two Mohos — not only a Seismic Moho, as just mentioned, but also a Petrological Moho, which pertains to a chemical change from mafic to ultramafic lithology. Sometimes the two coincide, sometimes not.

Figure 1 Idealised ophiolite sequence (Bristow 2004) overlaid with rock mineralogy (Kirk and Cook 1995).



© OUGS ISSN 2058-5209

Our first stop was to examine a gabbro outcrop at the northern end of Coverack beach (Fig. 2). This area represents the lower crust, above the Moho (*see* Fig. 1) and is within the top section of the geological sketch of Figure 2. Prof. Mather explained that weathered feldspar appears white, but when fresh the crystal can take on a blue-purple hue. We observed translucent crystals with hand lenses, some with a bluish tinge, but how much this was the result of the angle of the shining sun was a matter of debate.

Turning south we walked over a part of the beach strewn with boulders, some of which are worthy of mention. One such boulder appeared to have a dark gabbro within a matrix of a lighter

Figure 2 A geological sketch of Coverack Beach.

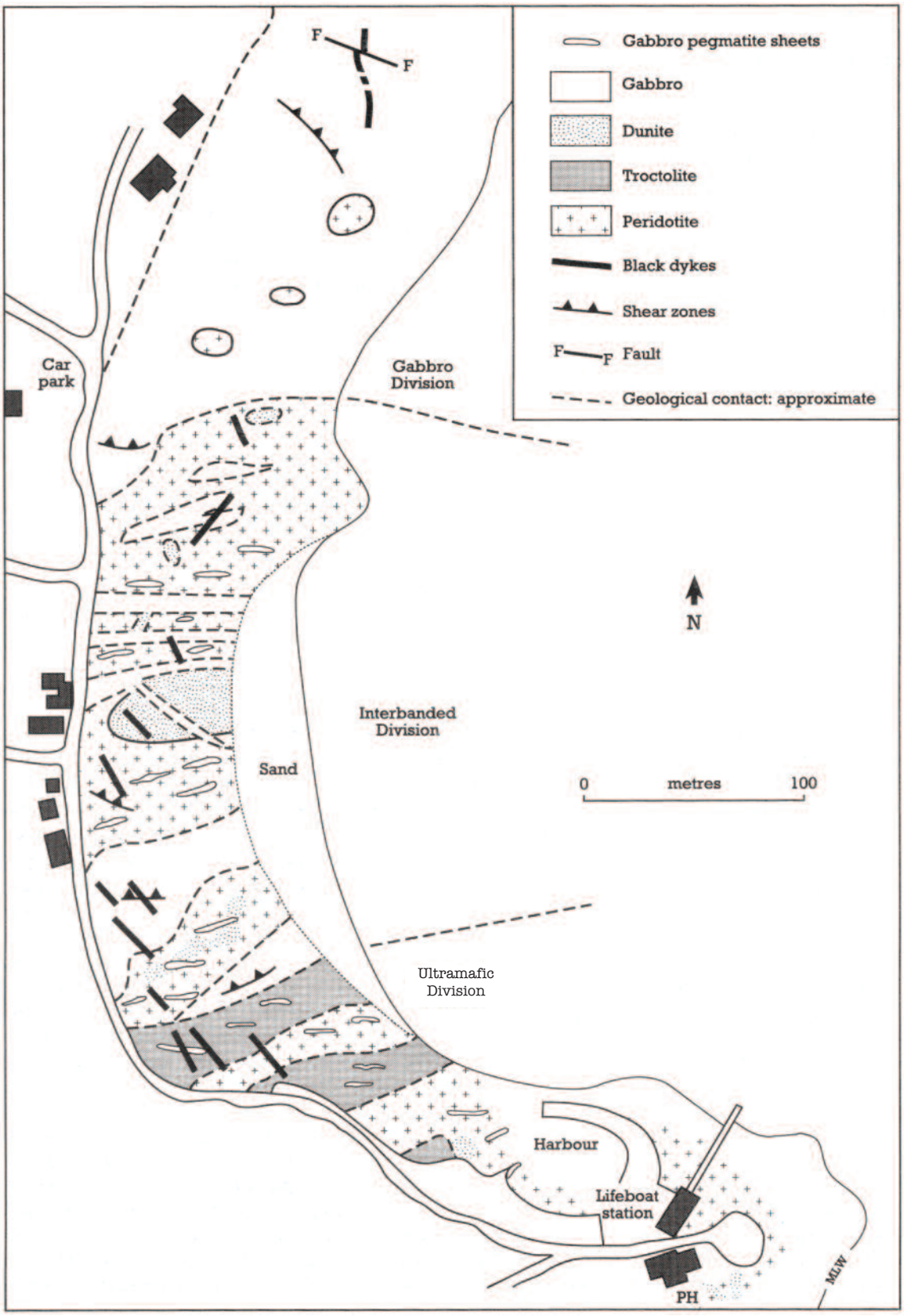


Figure 3 Brecciform gabbro on Coverack Beach.

coloured rock (Fig. 3). This texture is sometimes known as 'brecciform gabbro' in which the lighter rock — gabbro — has been altered over time to prehnite and the darker gabbro has remained unaltered.

Within the loose boulders we identified, *in situ*, a peridotite pod with olivine veins (Fig. 4). Such pods are often dunite (>90% olivine) that gets caught up in the gabbro. Another interesting nearby boulder — Figure 5 — displayed a chilled margin between peridotite (Fig. 5 *left*) and pegmatitic gabbro (*right*).

We next crossed into the Interbanded Division, the Moho, where we found a complicated assemblage of gabbro, dunite and peridotites cut through by basalt dykes of various sizes (*see* Fig. 2 *middle section*). We examined a highly polished exposure of peridotite abutting the sea wall (Fig. 6). On closer inspection we found that crystals within the peridotite had been lightly serpentinised, as evidenced by red patches. We also observed that the peridotite had been serpentinised where contact was made with the gabbro veins that spectacularly criss-crossed through the peridotite (Fig. 7).

Walking towards the harbour we came across good examples of 'lizard skin' rock, lightly serpentinised peridotite (Fig. 8a, *overleaf*), which can be compared to the 'trout stone' appearance of the rare rock troctolite (comprising mainly plagioclase and olivine; Fig. 8b).

Figure 4 A peridotite pod with olivine veins, Coverack Beach.

Figure 5 Peridotite (left) and gabbro (right) boulder, Coverack Beach.

Figure 6 Polished peridotite exposure, Interbanded Division, Coverack Beach.

Figure 7 Criss-crossing gabbro veins in close-up, Interbanded Division, Coverack Beach.

Figure 8 Examples of (left) serpentinised peridotite ('lizard skin') and (right) troctolite ('trout stone'), Coverack Beach.

Coverack is a classic locality for observing troctolite mingling with peridotite (Fig. 9). Troctolite olivine has been serpentinised to a dark red colour, which highlights the discrete pale plagioclase crystals, thus producing a distinctive mottled appearance. It appears that there is no known present-day volcanics that can be correlated to troctolite. Serpentinised troctoline olivine has also been identified within the cumulate layers of basic intrusions on the Island of Rhum, Scotland, but this does not appear to be an explanation for the exposures at Coverack.

Just a stone's throw south of this location was the Ultramafic Division of mantle peridotite (*see* Fig. 2 *lower section*). However, given the state of the tide and the wet rocks over which we would have had to clamber, we decided to return to our cars and drive to our next stop.

Godrevy Cove and Porthallow

Given the restricted vehicle access to Godrevy Cove, particularly to a fleet of at least seven cars, we parked in the village hall car park to the east of St. Keverne. Walking east to Rosenithon, we turned right onto a public footpath that took us through a wooded glad down to a deserted beach. We sat on rock sand ate our packed lunches, looking out to sea, which in the sunshine could be mistaken for the Mediterranean; then were ready to explore the next layer up the ocean crust of the ophiolite sequence — basalt dyke swarms.

Interpretating the dykes at this location was not easy. Figure 10 clearly shows a basalt dyke intruding dolerite. However, not 15m away, we observed a very mixed-up outcrop with white crystal veins of varying sizes trending in no particular direction

Figure 9 Troctolite mingled with peridotite, Interbanded Division, Coverack Beach.

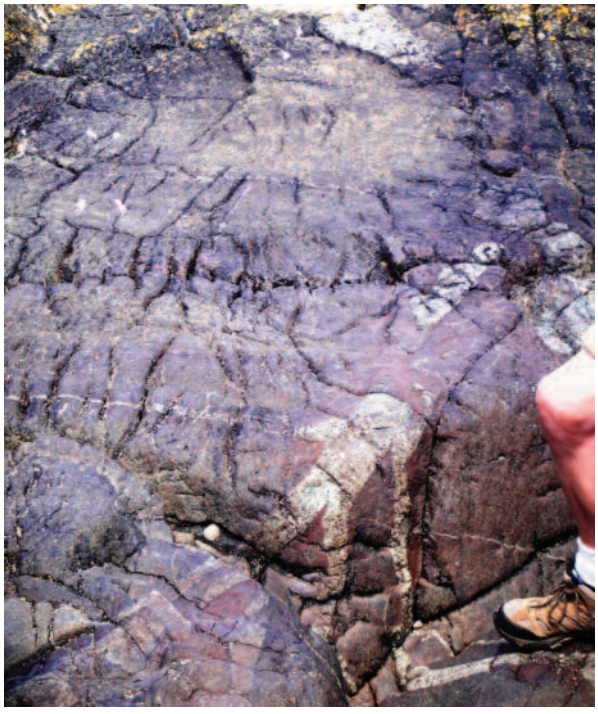


Figure 10 A basalt dyke intruding dolerite, Godrevy Cove.

(Fig. 11); and among the outcrops along the shore we observed several more dykes of varying widths with interesting contacts, but correlation between outcrops was difficult (Fig. 12, *overleaf*).

Dr Bennett was pleased to show us a raised, rounded-pebble beach (Fig. 13, *overleaf*). This exposure was thought to have formed *c.* 125,000 years ago. Although younger than the Lizard Head raised beach seen the previous day, it was exciting to have such an exposure only a few meters above today's high-water mark to provide evidence of changes in sea level overtime.

Unfortunately the next in the ophiolite sequence, pillow lavas, are not easy to access. Exposures can be seen at Mullion Island, which involves a boat, and at Nare Head, which involves a long walk. Therefore, our next stop was Porthallow, where the Lizard Boundary Fault on the south side of the cove denotes the end of the Lizard Complex and the beginning of the Meneage breccia to the north. Some of our party stayed to examine the rocks of the Lizard Boundary Fault zone, while others set off north along the South West Coast Path towards Turwell Point.

The Meneage breccia was formed as a pile of debris built up in front of the Lizard nappes as they slid down into the Gramscatho Basin to the North.

Consequently this area consists of well-cleaved breccia containing fragments of slate and other rock types, and much larger masses up — to 100m across — of various sedimentary, igneous and metamorphic rocks. Over time these rocks settled, as movement on the thrust ceased.

Figure 14 (*overleaf*) shows a distant view of the sloping meadow down to Turwell Point. The large white rock at the top of the grassy slope was identified as a quartzite of Ordovician age. We then clambered down the slope to inspect the rocks of an exposed breccia outcrop at sea level. Winding our way back along the South West Coast Path in the later afternoon sunshine to Porthallow was a fitting end to a very enjoyable day.

We thanked John and Jenny profusely for their time, effort and conviviality, and Michelle Thomas for her excellent organisational skills — even the weather behaved!

References

The majority of the factual information above was gleaned from Prof. Mather's narrative and the handout provided for the trip, which was based for the most part upon the first two references below.

Bristow, C. M. 2004 *Cornwall's Geology and Scenery*. St. Austell: Cornish Hillside Publication

Floyd, P. A., Exley, C. S., and Styles, M. T. 1993 Igneous Rocks of Southwest England. Geol Conserv Rev Ser No. **5**. London: Chapman and Hall (Images Figure 2: No. GCRv05c03f013 accessed on line 2.1.15): www.thegcr.org.uk/ImageBank.cfm?v=05&Style=Chapter&Chapter=03

Hall, T. 2005 *GA Guide to West Cornwall*. Geologist's Association Guide No. **31** (3rd edn)

Miller, T. 2008 'OUGS Walton Hall Branch field trip to the Lizard Peninsula 18–21 May 2007, led by Prof. John Mather and Dr Jenny Bennett'. *OUGSJ* **29 (1)**, 36–42

Kirk, Wendy, and Cook, David 1995 *Pocket Guide Rocks and Minerals*. London: Larousse

Figure 11 A conundrum? — A mixed-up outcrop comprising white crystal veins of varying sizes, Godrevy Cove.

Figure 12 Basalt dykes with interesting contacts, Godrevy Cove.

Figure 13 Raised pebble beach, Godrevy Cove.

Figure 14 Meneage mélange outcrops, Porthallow.

Field trip to the French and Italian Alps

(Mainland Europe Branch, June 15 to 21, 2014; led by Prof. Françoise Chalot-Prat, Univ. of Nancy)

Mark Biswell (London Branch), Elisabeth Davenport (East of Scotland Branch), Lilian D'Mello (East of Scotland Branch), Emmanuel Kavanagh (Mainland Europe Branch) and Stuart Swales (East of Scotland Branch)

Figure 1 Panoramic view, rift zone, rhyolitic cliffs (photo by M. Biswell).

Day 1 (June 16) Massif de l'Esterel

Mark Biswell

Stage 1 of the Wilson Cycle
Continental rifting — tectonic sedimentation and volcanism in the Permian 'Massif de l'Esteral'

On the first day we observed continental rifting from the Permian. The strata are lying with an angular unconformity on the Variscan basement, with lineations in a N–S orientation, the rift itself being E–W. The basement is composed of metamorphic and plutonic rocks. In this region we have fluvial sediments, ryholitic and basaltic volcanic sediments with rift structures and rifting processes.

Stop 1: *Base of the Permian succession, early continental conditions with fine fluvial deposits*.
Here we found a stratified outcrop with a channel, mostly fine sandstone interspersed with clay and a fining upwards sequence; also, wood has been found in some parts. This shows a braided river environment in a large fluvial channel. We inferred from this that there was a sluggish current in this location, indicating low relief on a gently sloping plain. The mature remnants of the eroded Variscan mountains have been deposited in streams within a peneplained region — this was a time of extended tectonic stability, where the tectonic plates were above sea level in equilibrium.

Stop 2: *Rhyolitic ignimbrites — pyroclastic flows (*nuée ardentes*)*
At this road cutting we saw two similar, well-defined units separated by a finer, darker layer. The two similar units were unsorted, with no internal structure and no flow banding, and appeared frozen before compaction. There are some voids where pumice has weathered out. Prof. Chalot-Prat explained that under thin section we would see broken glass shards, fragments of crystals and pumice with vesicles from 50mm to *c.* 1mm within a finer matrix.

© OUGS ISSN 2058-5209

This evidence shows that this rock is an ignimbrite, a deposit formed by the high temperature gas and pumice rich ash mix of a pyroclastic flow event. Ignimbrites are poorly sorted, with lapilli dispersed in an ashy matrix.

Pyroclastic density currents are referred to as 'flows' or 'surges', depending on particle concentration and the level of turbulence, and are also known as *nuée ardentes* (fiery clouds). The finer, darker volcaniclastic layer had no cross stratification, which would have classified it as a surge deposit; and it did not have enough visible stratification to classify it as an ash fall deposit. (Pyroclastic fall deposits consist of well-sorted lapilli with little ash.)

A compositional analysis revealed abundant quartz and alkali feldspar, showing that we had a rhyolitic ignimbrite. Rhyolites are more common and voluminous on the continents than in the ocean basins, and pyroclastic flow deposits spread out close to the eruptive vents. These observations led us to confirm that active continental rifting was taking place in the region.

Stop 3: *Basaltic lava flows*
At this road cutting, there are several lava flows that show an assortment of rounded and angular clasts, some with white/grey hyrothermal crystals formed via exolving gas percolating in the flow. The texture is fine-grained and crystalline with some phenocrysts of feldspar, pyroxene and augite — therefore a dolerite. Plagioclase occurs as sub-hedral tabular laths up to 2mm. There is visible haematite staining, possibly due to weathering of magnetite to a reddish brown.

We saw no olivine and no mantle xenoliths. There were several lava flows one after another, with no flow breccia from the breaking up of the cooling surfaces (i.e. aa lava) — all of the flows are dolerite and above them are fluvial sediments. We can speculate that the source was from dykes along the fracture to the north.

Prof. Chalot-Prat indicated that it is perhaps surprising to find a doleritic texture in a Permian lava flow and that trace elements show that we have here an intermediate calc-alkaline / pholeitic basalt that is typical of an alkaline basalt source.

We discussed two theories for the alkaline basalt formation: one, a hot spot from the lower mantle; and two, an alkaline basalt from the continental mantle lithospehere. Alkaline (intermediate calc-alkaline) basalts can come from the melting of continental lithosphere via decompression melting. This gives an intermediate signature, so perhaps comes from the base of the lithosphere close to the asthenosphere (the asthenosphere being the residue of the primitive mantle)? We concluded from the evidence that continental crust is being recycled in the mantle and that subduction of continental crust has occurred.

Stop 4: *Panoramic view, rift zone, rhyolitic cliffs*
From here we observed the rhyolite valley cliffs with their N–S extension (Fig. 1, *previous page*). Typical in rifted systems is that instead of having planar fault planes, the fault is curved. The fault surfaces we observed here are dipping into the valley. Prof. Chalot-Prat informed us that we have later sediments deposited in the basin of the valley, while the faulted walls of the valley are alternate deposits of sediment and rhyolitic deposits sitting uncomfortably on basement granite. This is a typical structure found in locations such as the North Sea Basin or the Rhine Valley.

Stop 5: *Late continental coarse detritic deposits*
Here we saw a series of conglomerate sandstone pebbles (from the Permian) and volcanic clasts. Prof. Chalot-Prat explained that the Permian sandstones layered with rhyolites were in relief, and exposed at the surface and eroded. The shoulder of the rift was uplifted, resulting in layered sediments being deposited as the rocks at surface were being weathered.

We deduced that the relief was forming during active phases of sedimentation and volcanism — the uplift was contemporaneous with the sedimentation and volcanism. At the large scale a slight uplift of the lithosphere occurred of *c.* 1,500m, during extension. Decompression melting forced the uplift but the exact model of its behaviour is not clear.

Stop 6: *Late continental deposits — arenaceous deposits*
Some stratification is visible here in this, an arkose textured unit from fluvial flows in channels. These are locally formed volcanic sediments, formed by the alteration of granite in a tropical climate, creating a volcanic arenite. The tropically weathered granite has been transported in a mass flow locally and likely has a quartz cement. These strata represent local mass-flow transportation via fluvial action from the uplifted shoulder of the rift.

Day 2 (June 17) Esclangon Massif

Elisabeth Davenport

On Tuesday we continued our exploration of the Wilson Cycle in a visit to the Esclangon Massif, where we saw the effects of both continental extension (Stage 2) and continental collision (Stage 5a) on the western margin of the collisional system.

The Massif consists of two main units: the lower one is autochthonous and consists of Mesozoic to Cenozoic folded sediments (the relationship is one of angular unconformity). The upper unit of the Massif overlies the lower unit in a major thrust fault, the Nappe de Digne.

The context
During continental extension, the Mesozoic formations of the lower unit (Trias to Cretaceous) formed on the western margin of a marine continental basin. The Mesozoic formations of the upper unit, the Nappe de Digne (Trias to Lower Jurassic), represent distal marine deposits laid down with those of the lower unit, just before the opening of the ocean (Stage 3 of the Wilson Cycle).

During continental collision, the Mesozoic formations were strongly folded, and those of the upper unit were detached and included in the nappe that was thrusting south-westward. The Cenozoic sequence of the lower unit consists of detritus deposited and folded as topographic relief developed in front of the moving nappe, giving the unique and spectacular structure of the Velodrome de l'Esclangon. These sediments (molasse) are continental (Eocene to Oligocene) and later marine (Miocene to Pliocene) and represent the erosion products of the mountain range during the collision stage.

Our objective was to reconstruct through our field observations the tectonic structure of the collision stage and to understand the relationships between tectonics and sedimentation on this western margin of the orogenic cycle in its later stages.

Figure 2 Eocene breccia (photo by S. Swales).

Our observations

Locality 1: At the Clue du Peroure, we observed reddish vertical Eocene breccia abutting low-angled, yellowish beds of alternating laminate and massive material (Fig. 2).

The beds here are inverted, as thick Jurassic limestone beds (Tithonique) lie on top of the Cretaceous; the latter is the source of angular fragments in the breccia. Small shear structures in the thinner beds confirm the inversion. The Eocene breccia is localised detrital molasse in front of an authochthonous fold, formed before the Upper Cretaceous, as there are no rocks of this age here. Prof. Chalot-Prat retro-engineered the genesis of the locality stage by stage to take us back to the passive margin of a Jurassic–Cretaceous marine basin.

Locality 2: As we ascended to the Bayeul summit we saw evidence of fluviatile (root traces and mud-filled holes) (Fig. 3) and marine environments (blackened laminate with de-watering structures) (Fig. 4). There was renewed marine progression in the Miocene, as uplift was less than subsidence.

Locality 3: At this elevation, we could appreciate the structure of the thrust at map scale, with large triangular blocks of Jurassic dragged along beneath it like contact breccia, overlain by stratified purple and ochre Trias (this contains gypsum, a major lubricant for the nappe) and by Lower/Upper Trias that has been

Figure 3 Root traces and mud-filled holes (photo by S. Swales).

transported east, and grey Lias sediment above the Trias, all deeply folded in three dimensions (Fig. 5, *overleaf*). Below the contact we observed a recumbent anticline (we were looking down the hinge) plunging beneath Eocene–Oligocene strata. This hog-backed structure is composed of the beds that we examined in Locality 1; it was an instructive example of how important three-dimensionality is in structural geology.

Locality 4: At Bayeul summit, the erosion of the nappe has resulted in a tectonic window, the Velodrome, which reveals the heavily folded and inverted multiple beds of a vast fluvial fan system (Fig. 6, *overleaf*). These deposits were folded in the process of sedimentation, and in-filled basins were created by buckling, a process intensified in the mid-Miocene, as the Adriatic plate pushed the sea floor sediments, resulting in a fold with vertical limbs in this locality, which was later overturned by the nappe to produce a reverse syncline.

As we ate our sandwiches, thunder, lightning and torrential rain burst over our heads — this storm had been threatening most of the morning. Our final exercise, the drawing of a cross-section integrating sedimentation and tectonics was abandoned, and we beat a rapid retreat.

Locality 5: At the final locality we inspected the Dalle d'Ammonites, a continuous slab of Lower calcareous Lias at the

Figure 4 Blackened laminate with de-watering structures (photo by S. Swales).

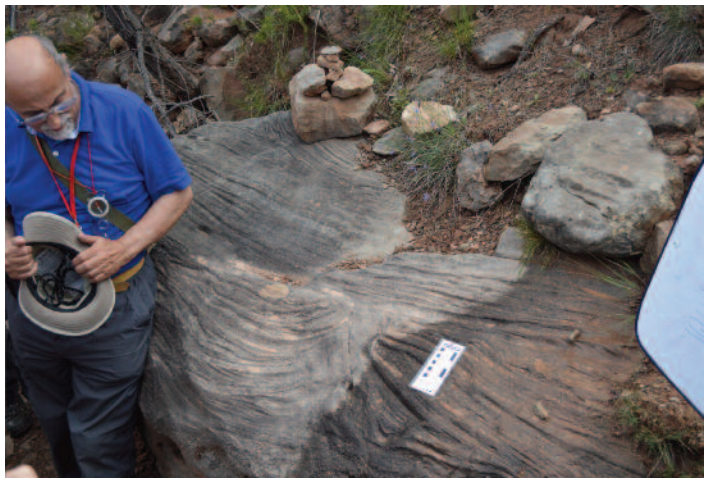


Figure 5 Autochthonous molasse rouge below nappe de Digne; allochthonous creamy Triassic up through Lias (grey skyline); Tithonian fragments along tectonic contact (photo by S. Swales).

Figure 6 View to west from Esclangon summit. Vélodrome Miocene (grey) and Pliocene (ochre) molasse (photo by S. Swales).

Figure 7 Dalle à ammonites, Digne-les-Bains] (photo by S. Swales).

foot of the Digne nappe (Figs 7 and 8). The steeply dipping bedding planes are covered with more than 1,500 ammonites, including Arietites, and are part of the distal sediments transported by the thrust.

Day 3 (June 18) Saint-Véran

Lilian D'Mello

From oceanic plate spreading to oceanic plate subduction

An amazing day despite the snow and cold, but a very welcome lunch and hot chocolate stop in the little refuge by Lac Blanchet. Stunning views from this vantage point!

We started from the car park a few miles from the village. We passed a disused marble quarry and just a little farther on we passed a copper mine. Not far past these places we saw our first blueschist.

The context

The St Véran area, from Chapelle de Chapelle de Clausis to Lacs Blanchet (Fig. 9) consists of upper Jurassic (160–150Ma) series of sedimentary, magmatic and mantle rocks representative of the uppermost part of the oceanic lithosphere. This ophiolite is metamorphic (high pressure-low temperature Blueschist facies), and more or less folded.

Figure 8 Close-up of ammonites at Dalle à ammonites, Digne-les-Bains (lenscap for scape) (photo by S. Swales).

The plate tectonic context

The St Véran area belongs to the oceanic suture, the formations of which were subducted and strongly metamorphosed during Stage 4 of the Wilson Cycle, then exhumed and retro-morphosed during Stage 5 of the orogenic alpine cycle. This oceanic unit is representative of the bottom of the ocean, named 'Alpine Tethys', during active oceanic spreading during the Upper Jusassic.

Our field observations

Along the trail, as we faced the Chapelle de Clausis to the Lacs Blanchet, we observed different highly metamorphic textures and mineral assemblages within mantle, gabbro, basalt, limestone and flysch, and tried to decipher their metamorphic paths and their original geometic relationships within the oceanic lithosphere.

The blueschist as a rock type is defined by the presence of the minerals glaucophane (Figs 10 and 11, *overleaf*) + (lawsonite or epidote) +/- jadeite +/- albite or chlorite +/- garnet +/- muscovite in a rock of roughly basaltic composition. It often has a lepidoblastic, nematoblastic or schistose rock microstructure defined primarily by the chlorite, phengitic white mica, glaucophane and other minerals with an elongate or platy shape within it.

All in all, a very interesting day and we wondered if it could any get better ... it did!

Figure 9 Basalt cliffs above Lac de la Blanche, Aigue Blanche valley (photo by S. Swales).

Figure 10 Metagabbro: Augite with glaucophane rim, Aigue Blanche valley (photo by S. Swales).

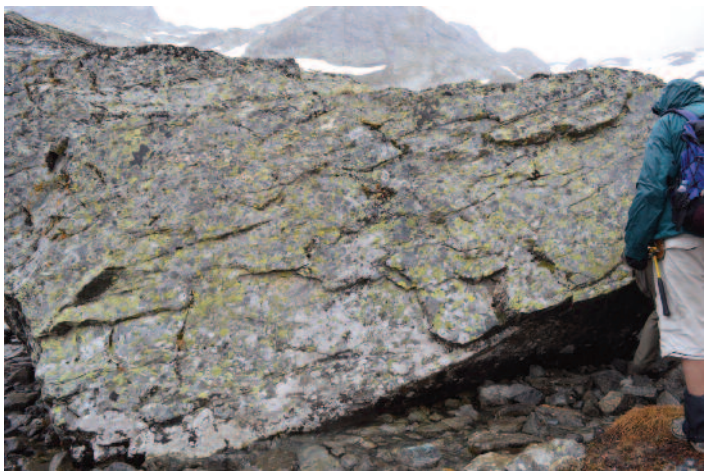


Figure 11 Blueschist facies basalt pillows, Aigue Blanche valley (photo by S. Swales).

Day 4 (June 19) Chenaillet Massif

Emmanuel Kavanagh

Having spent the night (Wednesday) in Claviere just over the Italian border, we headed back into France on Thursday morning to start what would be our most physically challenging day of the field trip, with the aim of identifying evidence for oceanic rifting and subsequent continental collision as part of our continued exploration of the Wilson Cycle.

The Chenaillet Massif is a remarkably undeformed, obducted Upper Jurassic ophiolite which forms a nappe overlying the St Véran area that we had visited the previous day. It belongs to the Alpine orogenic suture and represents the collision stage of the Wilson Cycle, with the ophiolite itself representing a slow-spreading ridge similar to the Atlantic ridge.

Our first stop was to observe a pile of pillow lava tongues, indicative of subaqueous extrusion of lava (Fig. 12). We observed it perpendicular to the flow direction and Prof. Chalot-Prat described their size, geometry and features, as well as getting us all to draw sketches of what we saw — always a useful skill to develop for a geologist.

Our next stop was to observe more pillow lavas, but this time they were visible parallel to flow direction and so we were able to see their shapes from another angle, a viewpoint that highlighted their shapes as tubes flowing on a slope (Fig. 13). By combining our observations with those made at the first stop we were able to get a good understanding of the shape and movement of pillow lavas in three dimensions. We also saw spherulites, and this sparked a lively and interesting discussion about their use as a diagnostic feature — Prof. Chalot-Prat explained that their distance from the rim of the pillow lavas was related to the speed of quenching of the lava. We also observed pillow breccias, showing pillows broken apart by fractures. Such features usually occur on the steeper slope near the vent, while whole pillows are preserved on the gentler slope. Finally, the spatial relationships between tongues were used to determine the relative ages of different pillows.

The third stop was a contact between gabbro and basalt, with the sinuous contact between the two cited as evidence for the gabbro still being relatively plastic when the basalt dykes cut across it.

After a steep climb and a welcome rest for lunch, our next stop was for banded gabbro (Fig. 14, *opposite*), where we observed both brittle and ductile deformation. These kinematic indicators enabled us to determine a sense of movement in the shear zone. Both the mylonites and cataclasites were present, forming part of a detachment fault, which would explain both why these ductile and brittle deformation features are present and how the gabbro arrived at the surface.

These detachment faults were dated 155Ma in the Middle to Upper Jurassic, and the fact that they had been recently exhumed explains the sinuous contact with the basalt dykes

Figure 12 Pair of pillow tongues descending from right (photo by S. Swales).

Figure 13 Pillow lava tube (photo by S. Swales).

Figure 14 (above) Banded gabbro (photo by E. Kavanagh).

observed at the previous stop. The source of the basalt, however, was not fractional crystallisation, but rather had a deeper origin and was tholeiitic.

The fifth stop was to observe some peridotite breccia within a calcareous mudstone, and here we found evidence of cross-bedding due to strong currents at the mid-ocean ridge, as well as sedimentary deposits of serpentine sand. The sixth stop also took in some sedimentary features, with talus breccia made by weathering of the mantle following exhumation along a detachment fault.

Our next stop took us atop the Chenaillet Massif itself (Fig. 15), where we took a moment to catch our breath, take in the amazing views and pose for a group photo (Fig. 16). Prof. Chalot-Prat showed us the tooth and comb features: a series of dykes form the teeth of the comb, and were visible parallel to each other, the oldest down-slope and the youngest up-slope. These 'teeth' are oriented perpendicular to the branch of the comb.

Figure 15 Chenaillet summit and comb volcanic system (photo by S. Swales).

Figure 16 Group photo on Chenaillet summit (photo by F. Chalot-Prat).

Figure 17 Falaise du Collet Vert: vertical cliff face composed of in situ *pillow lavas and dykes (photo by E. Kavanagh).*

Prof. Chalot-Prat explained that with students she took samples from the different dykes along the sequence and that the geochemisty of the parallel dykes matched, providing solid evidence that what we could see was indeed an undeformed section of a mid-ocean ridge.

After coming down from the Chenaillet Massif we made our way to the final stop of the day, the Falaise du Collet Vert where we observed a vertical cliff face composed of *in situ* pillow lavas and dykes (Fig. 17). This wholesale displacement of a pillow lava sequence can be explained by exhumation of the mantle.

Following a long but rewarding day in the Chenaillet Massif where Prof. Chalot-Prat had showed us some remarkable geological features, we made our way back to our hostel for some well-earned rest.

Day 5 (June 20) Ivrea Massif

Stuart Swales

Setting off early in the morning we whizzed across northern Italy from Sestriere past Torino to the small town of Varallo, west of Lake Maggiore. The bulk of Gran Paradiso, one of the major Internal Crystalline Massifs of the western continental margin, dominated the northern horizon as we crossed the Piedmont plain. Also visible from here was the distinctive peak of Monte Viso, which is composed of ultra-high pressure rocks such as eclogite. These were part of the Internal Zone of the western margin, which sadly we had to omit on this trip. Leaving our overnight things at the hostel in Varallo we then set off westward, up the Val Sesia, for the day's hands-on geology.

The first stop was just east of Balmuccia village. Here, at lunch, Prof. Chalot-Prat explained more about the setting of the Ivrea Zone, which is a nappe of the eastern continental margin that contains some subcontinental mantle rocks, above which are large (40km long × 10km thick) gabbro bodies of Permian age. As everything has been folded, the gabbros may have been thinner originally, but still probably 7km thick. Above these, and to the east, granulitic lower crust is present.

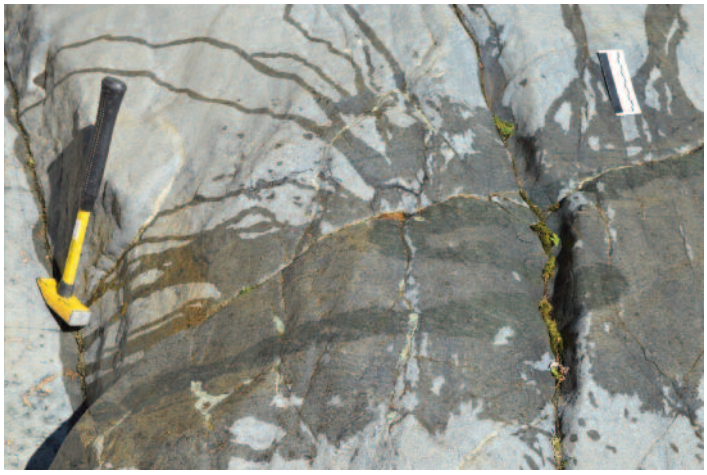
Finally, one would find the upper crustal units with Permian granites and volcanics — also with Permian rift sediments, as we saw on the first day on the Esterel Massif. It is believed that the deeper rocks (mantle and granulite) of the Ivrea Zone were uplifted to higher crustal levels towards the end of the Variscan Orogeny.

Going down rocks and a ladder to the River Sesia, an exceptional riverside outcrop of ochreous mantle is revealed, well polished by water when the river runs high. The mantle rocks were veined by grey-green and grey-brown veins generally up to 100mm wide (the largest seen was 200mm wide), mostly subparallel, with some cross-cutting at low angles (Fig. 18). Splashing water on the rocks helped to improve the contrast and see the colours better, though with it being such a lovely hot day the water quickly evaporated!

The edges of the veins were not as sharp as first thought, showing blending with the host rock. The 3D nature of the outcrop showed that the veins were pervasive and vertically extensive through the outcrop. Small-scale faults could be identified where they had displaced the veins; however, few faults seemed to displace more than one set of veins. Some of the veins exhibited small-scale open folding, and a schistosity could also be discerned in some of the veins. Some veins thinned and bulged across their length, with one wider vein abruptly terminating in a sharp butt-end.

Prof. Chalot-Prat explained that the different colours of the veins reflected their differing compositions. The greener veins were largely diopside (clinopyroxene) with some spinel and some enstatite. The greyer veins had an enstatite (orthopyroxene) matrix with many 10mm-scale black clots of spinel. Rarer veins

Figure 18 Veined ochreous Balmuccia mantle peridotite along the River Sesia (photo by S. Swales).



with sinuous contacts contained black amphiboles — possible metasomatism?

The mantle host rock here is peridotite (Fig. 19). Analyses had shown this to be approximately 70% olivine, 20% diopside and 10% enstatite — i.e. a lherzolite, but locally varying to harzburgite; and there are mm-scale square and rectangular brown phenocrysts on weathered surfaces. The olivine was weathering to an ochre colour, but surprisingly (to me at least) was shown to be clear grey to black in fresh samples. As in their corresponding veins, the diopsides were green and the enstatites clear grey. There is also apparently a little spinel to be found in the peridotite, but it is microscopic. Closer inspection of the peridotite close to the edges of veins showed scattered phenocrysts that have been derived from the corresponding vein (Di/En).

The second stop of the day was a short distance downstream from the first, and was intriguingly labelled 'Supervolcano' at the car park — it is apparently a quite new UNESCO Geopark (see www. supervulcano.it). We wandered along a wooded path to another excellent riverside exposure, this time of a layered gabbro (Fig. 20).

This rock had an isotropic texture in places, being well zoned in others, and was composed of brown amphibole, augite and plagioclase feldspar. The phenocrysts are best seen in the non-layered zones with euhedral amphibole 'lozenges', augite 'sticks' and xenomorphic plagioclase feldspars. The most common layering seen on this outcrop showed a sharp-based dark layer grading up into lighter, more plagioclase-rich, layers of *c.* 100–200mm.

Quite striking were the tight-to-isoclinal folds, with the layers thinned on the fold limbs (Fig. 21). These folds apparently have similar axes to those seen in the mantle rocks of the first stop. One large fold had developed an axis-parallel schistosity in the gabbro.

We discussed the calcic nature of the brown amphibole and augite and thought that it was most likely that the plagioclase would be quite calcic too, giving a gabbro. Looking carefully at the sharp-based dark layers again, we found that sometimes it was augite-dominated, sometimes predominantly brown amphibole, which led onto a revisiting of ternary phase diagrams and how the first crystals to form from a liquid can be quite sensitive to the original bulk composition of the gabbro's parent magma (Fig. 22, *overleaf*).

Magmas of gabbroic composition have a low viscosity (unlike silicic magmas) and so enable crystal settling as seen so clearly here. The plagioclases in this gabbro were always crystallising last, surrounding and penetrating interstices between the euhedral mafic minerals (hence the designation xenomorphic).

Figure 19 Balmuccia mantle peridotite, Val Sesia (photo by S. Swales).

Figure 20 Layered gabbro near Isola, Val Sesia (photo by S. Swales).

Figure 21 Layered gabbro showing isoclinal folding, Val Sesia (photo by S. Swales).

Figure 22 Prof. Chalot-Prat explains gabbro layering with ternary diagram (photo by S. Swales).

Prof. Chalot-Prat told us that this particular gabbro body was *c.* 30km long and 7km thick. She also explained that many of the gabbro bodies in the Ivrea Zone were intruded sideways, as thick sills along detachment faults — which has been confirmed by geophysical investigations — and not as bottom-fed plutons. This is likely to be related to the Permian rift-initiation processes as seen in the Esterel on the opposing margin of the eventual rift.

We concluded the visit to this stop by wandering upstream examining the profusion of different types of rocks brought down in boulder form by this powerful river. We found many gneisses, granitoids and schists, but I think we were unlucky not to find any eclogite (Fig. 23).

At our group evening meal in Varallo we took the opportunity to profusely thank Prof. Françoise Chalot-Prat for the wonderful field trip and Elisabeth d'Eyrames and Beatrice Will for their excellent organisation and driving. Well done everyone involved! My own thanks go to everyone on this trip for the good company and interesting and stimulating discussions we had during this week.

Figure 23 More Balmuccia mantle peridotite, Val Sesia (photo by S. Swales).

Cliviger Valley, Yorkshire–Lancashire

(led by Paul Kabrna of the Craven and Pendle Geological Society)

Ricky Savage

On the morning of the 12 July 2014, members of the Yorkshire Branch of the OUGS met up with Paul Kabrna of the Craven and Pendle Geological Society, at the lay-by just off the A646. At Locality 1 Paul explained the geological setting of the area.

The Cliviger Valley straddles the border between Yorkshire and Lancashire and its head marks the watershed of the drainage basins of these two counties (Fig. 1). The valley was formed by the incision of glacial meltwater from previous ice ages. This melt water has caused a striking topography. The removal of rock by the action of the water has left numerous, well-exposed exposures, for example tributary streams left 'hanging' on Thievely Scout. It is also this action that produced numerous natural exposures of Carboniferous rocks.

The area comprises two main Carboniferous units: the Namurian Millstone Grit Group and the Coal Measures, both units commonly associated with Pennine geology. In this area they are ordered into successions called cyclothems, which are formed by the repeated construction of sandy deltas into deep-water basins (Wignall and Kabrna 1996). An ideal cyclothem is seen in Figure 2, and would be repeated over many cycles. Wignall (1996) and Wanless (1957) both agree that cyclothems are rarely ideally developed.

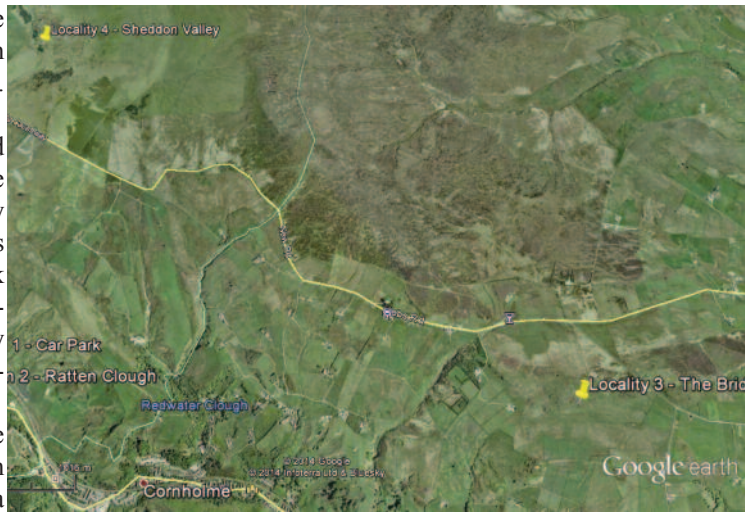


Figure 1 Map with visited localities (Image Courtesy of Google Earth, Getmapping plc. Infoterra Ltd & Bluesky © 2014).

To summarise the process of formation of cyclothems further, organic matter collects on a delta top, then there is a transgression of seawater, and deposition of sand and mud on top of the organic matter. This process is repeated many times, so each cyclothem consists of marine and non-marine layers. This is certainly what we saw at Locality 2.

Walking up from Locality 1 to Locality 2, the group came to the first exposure of the day. The exposure demonstrated a number of lithologies and these were: (1) Holcombe Brook Grit, which is in the river bed, (2) a layer of fireclay beneath (3) a thin shaly black seam of coal, and above this (4) a non-marine bed of shale (Fig. 3, *overleaf*). We saw the Lower Kinderscout Grit again later in the day.

Twenty-five metres higher, on Ratten Clough, another exposure of tougher black shale contained the goniatite, *Gastrioceras cancellatum* (Fig. 4, *overleaf*). Namurian black shale marine bands represent maximum flooding events, and were deposited during glacio-eustatic high-stands.

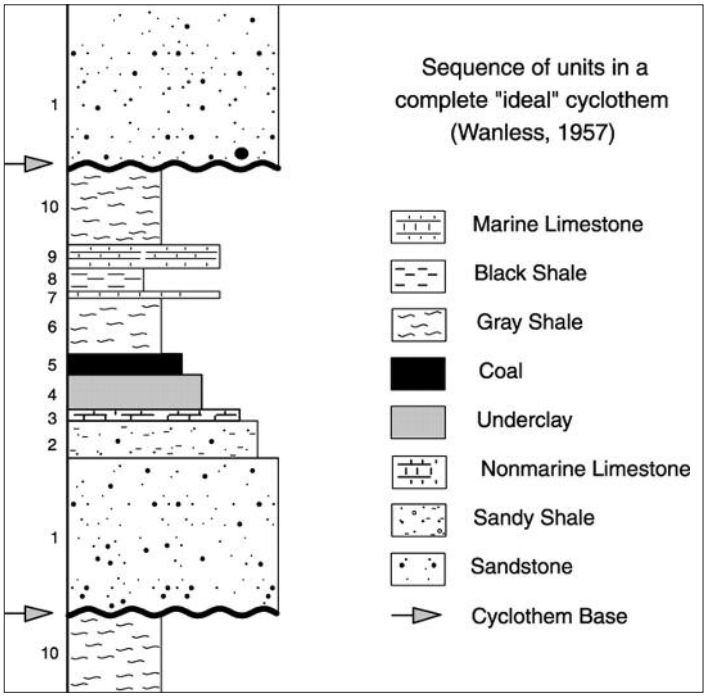
Goniatites are ammonoid-shelled cephalopods related to squids, belemnites, octopuses and cuttlefish, and more distantly to the nautiloids. It is generally accepted that the coiled ammonoids originated from a group of uncoiled cephalopods in early Devonian ammonoid species. They lived during the Middle Devonian some 390 million years ago. Goniatites flourished during the Carboniferous and Permian, but at the end of this period they became extinct.

The ammonoids all possessed an external shell, which is divided internally into chambers. The animal lived in the last, open-ended chamber, and the internal chambers were filled with gas, making the animal buoyant in the water. They were free-swimming animals, possessing a head with two well-developed eyes and arms (or tentacles). The fossils that we found were *c.* 25mm in size. An article in Wikipedia (2014) states that they are "almost always less than 15 cm (5.9 in) in diameter and often smaller than 5 cm".

Free-swimming goniatites had a global distribution making them ideal zone fossils for correlating rocks. They were reliant on marine conditions, but inhabited inland seas rather than the open ocean. They were often found in basinal environments and deeper offshore, rather than next to the shoreline.Their occurrence in marine bands of the Carboniferous Millstone Grit Group and Coal Measures in Europe make them the ideal diagnostic tool for the biostratigrapher.

While looking at the marine band, blocks of Rough Rock from the top of Ratten Clough contained abundant calamite stems

Figure 2 Example of an idealised cyclothem (Wanless, 1957).



© OUGS ISSN 2058-5209

Figure 3 showing the four distinct lithologies (photo by R. Savage).

(giant horsetails) in an *ad hoc* array, suggesting that they were deposited in log jams.

On the way back down to the car park at Locality 1, we stopped, sat down and Paul asked us to look at the topography. We looked across at the opposite side of the valley, and the first feature noticeable was a series of ridges dipping gently in a westerly direction, at approximately 25˚. These represented the expression of a series of Coal Measure cyclothems. In Figure 5 you can clearly see the railway, which marks the point of the

Figure 4 A goniatite, Gastrioceras cancellatum*, found at Ratten Clough (photo by P. Kabrna).*

Cliviger Valley Fault. In this area, the northern side of the fault has a downthrow of 280m (Hough 2004). In Figure 5 you can also see spoil heaps — the remnants of ironstone mining on Riddle Scout.

In the afternoon we drove to Locatity 3, which was called the Bridestones. The rock face itself was *c.* 5m high. The Upper Kinderscout Grit or Gritstone was weathered and evidence of erosion present. As this was an exposed moorland location, the gritstone would be susceptible to the south-westerly wind, rains and harsh winter frosts, which would further erode the cliffs (Fig. 6, *opposite*). There was also a rock *c.* 4m tall, not as tall as the cliffs, shaped like a pedestal and standing on its own *c*. 4–5m away from the cliff. The cliffs showed signs of cross-bedding and indicated that when the grains were deposited there was a flow regime typical of river deposits or tidal areas in a prograding delta environment. Some of the cross-bedded structures were truncated; this shows that a flood had eroded some of the deposits and then a new bed formed over the original deposit.

This was the Upper Kinderscout Grit that was seen at Locality 2, at the base of the exposure. When the group left Locality 2, and the Holcombe Brook Grit beneath the fireclay, we were at *c.* 197m above sea level. We had driven up a large hill to the Roman road

Figure 5 Railway in middle is in line with the fault, dipping cyclothems at top left corner, and hummocky topography is due to the lead mining in the area (photo by R. Savage).

Figure 6 The Bridestone cliffs (photo by R. Savage).

known as the Long Causeway, and the Bridestones were at 415 m above sea level. So how could this be Upper Kinderscout Grit? As we were driving up the hill to get to Locality 3 we were actually driving up an anticline (Fig. 7).

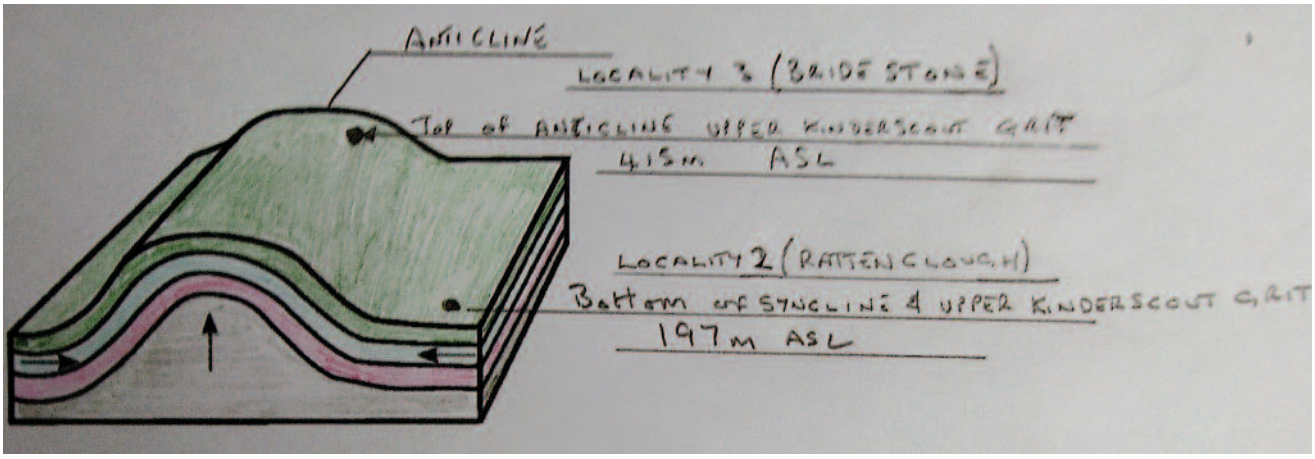
Our final stop of the day was at Locality 4, the limestone hushings at Sheddon Valley. The hushings are the remnants of a 16th-century industry based on the extraction of lime from the local limestone. It was at this time that the building trade took a significant step forward by replacing timber and wattle-and-daub buildings with stone structures, hence the demand for lime (for the mortar between building stones).

What was strange about this limestone hushing was its location, as there was no bedrock source of limestone. The limestone boulders here were sourced from erratics found in boulder clay. In the last period of glaciation, limestone would have been picked up in the ice sheets from the Yorkshire dales and Ribblesdale. The glaciers over time transported them to the area, *c.* 10,000 years ago.

A few months ago our branch visited Mappleton on the Yorkshire east coast and we saw boulder clay, where trying to extract odd bits of rock was quite difficult at times; so this gave me an understanding of how difficult it would have been to remove large boulders of limestone out of this boulder clay. Therefore people used a technique called hushing to make the process easier.

Hushing involves releasing stored water and allowing the energy from this to clear away the boulder clay, leaving the limestone. Builders would then break up the boulders until all the pieces

Figure 7 Diagram of the anticline we climbed (photo by R. Savage).



were 100–150mm. They loaded the kiln with layers of limestone, then coke, then more limestone. The limestone would need to reach a temperature of 800˚C inside the kiln (Fig. 8). The fuel for kilns came from the local coal measures.

The group enjoyed the field trip led by Paul Kabrna and the branch is looking forward to having another trip led by him sometime soon.

Figure 8. Disused kiln at Sheddon Valley Limestone Hushings (photo by R. Savage).

References

Hough, E. 2004 *Geology of the Burnley Area (SD82NW and SD83SW)*. British Geological Survey Internal Report **WA/00/30**. Keyworth: BGS

Wignall, P., and Kabrna, P. 1996 'Excursion 8: The Carboniferous (Namurian and Westphalian) of the Cliviger Valley, Todmorden', *in* Scrutton, C. (ed.) *Yorkshire Rocks and Landscape* (3rd edn). Maryport: Ellenbank Press / Yorkshire Geological Society, 84–91

Wanless, H. R. 1957 *Geology and Mineral Resources of the Beardstown, Glasford, Havana and Vermont Quadrangles*. Champaign, Il: State of Illinois Geological Survey

The geology of Mourne, Cooley and Gullion, Counties Louth and Down

(Ireland Branch field trip 6–7 September 2014; led by Dr Siobhán Power)

Isabel O'Brien

Introduction

On this fascinating trip, our OUGS Branch was introduced to the Mourne-Cooley-Gullion Geotourism Project, an innovative initiative created to bring international attention to an area of the unparalleled geological and archaeological importance. The region comprises the Mourne Mountains, the Cooley Peninsula and the Ring of Slieve Gullion. While the project also includes the region's cultural heritage, we only looked at the geology this time, but we will definitely be back for more!

Our leader was Dr Siobhán Power (Fig. 1), an enthusiastic geologist from Glenamaddy (Co. Galway). Having graduated with a BSc in Earth Science from the National University of Ireland, Galway (NUIG), Siobhán pursued a PhD in Geology, also in Galway, studying field relations, joint analysis and fluid inclusions on the late structural history of the Connemara Dalradian. Her post-doctoral research took her to the University of Iowa, USA, where her research was based on ultrahigh-pressure metamorphism in the Caledonides, which involved spending more than six weeks doing field work in north-east Greenland. After this endeavour, Siobhán taught geology at Liverpool John Moores University for seven years before returning to Ireland. In early 2013 she began to work as a geologist with Mourne Cooley Gullion Geotourism.

Figure 1 Dr Siobhán Power, Mourne Cooley Gullion Geotourism.

Saturday 6 September

Our trip started at 10.30 a.m. meeting at the Carrickdale Hotel and Spa, just off the M1, where a good number of members from both sides of the border had gathered. And we were even joined by our littlest member, Master Max Rice, not even a year old!

Overview from Black Mountain

Our first stop was just a few kilometres from the hotel, the summit of Black Mountain (Clermont Carn, home to the RTE transmitter for NE Ireland). From there we were able to enjoy a 360˚ view of the different igneous complexes and the landscape around us. Needless to say, the outstanding beauty of the region could easily be appreciated up there! Figure 2 (*overleaf*) shows an overview of the bedrock geology of the Mourne Cooley Gullion region.

The three igneous complexes formed 60Ma ago during the Palaeogene and sit on top of Silurian metasediments, in a story that spans millions of years from 430Ma ago to the relatively recent action of the ice during the last glaciation 10,000 years ago. Simply stated, the region shows the scars of some the most dramatic geological events that ever happened in Ireland, which Dr Power referred to as 'the tale of two oceans'. The processes that occurred as consequence of the closing of the Iapetus Ocean can be witnessed in the region: the suture zone exposed in Clogher Head south of Dundalk; an accretionary prism created during this subduction event, which forms the Longford–Down Inlier; and finally, but not least, the associated igneous activity of the Newry Igneous Complex in the form of granodiorite plutons intruding into the country rock. After a gap of *c.* 260Ma, the opening of the North Atlantic was the next event that left an imprint in the landscape, since the stretching forces resulting from the landmasses pulling apart caused the thinning of the crust, allowing the intrusion of the three large igneous complexes that formed the core of our field trip.

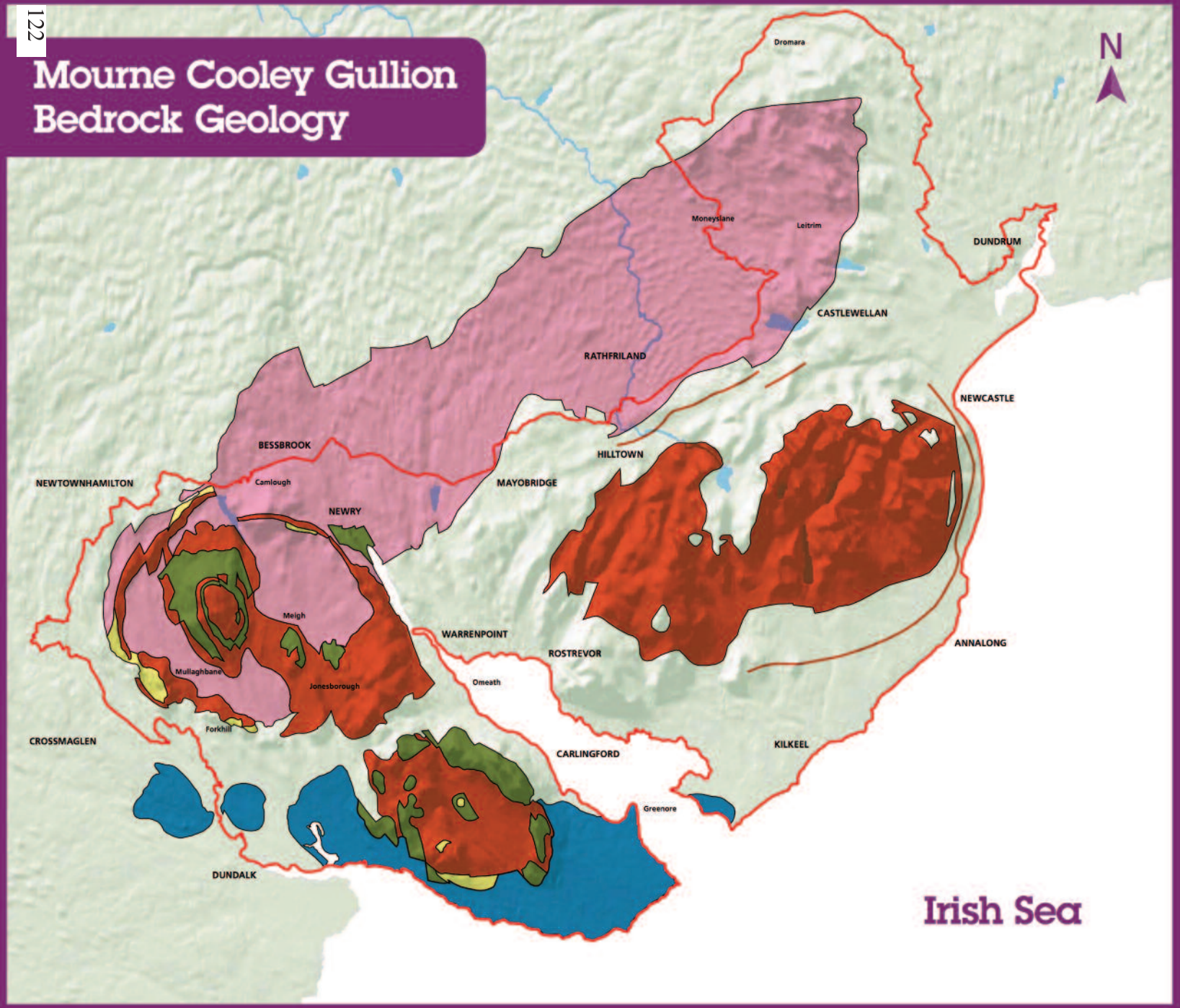
The Carlingford Complex is the oldest of the three igneous intrusions, and therefore the first to develop 61Ma ago. The Ring of Slieve Gullion is mostly younger than Carlingford, 58Ma, with some overlap; the ring has the peculiarity of having been the first ring dyke to be described. The Mourne Mountains Complex is the youngest of the three, intruded 56Ma ago. Here in the mountains is where the action of the ice during the last glacial event can be observed, such as in the glaciated valleys.

From the Black Mountain we could also observe the Mourne plains that extend from the foothills to the sea, all agricultural fields harnessing the richness of the Silurian metasediments. The Carlingford Lough could also be viewed in full from our vantage point, and we were told that it is a drowned, shallow glaciated valley. So despite hinting so in its name, Carlingford Lough is not a fjord, because it is not deeper than the Irish Sea.

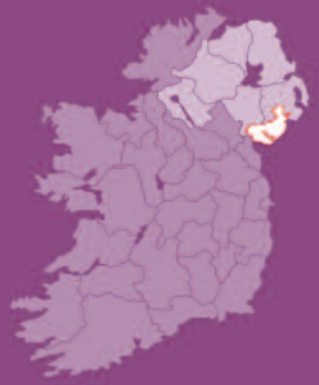
The Carlingford Complex

We drove down Black Mountain through a windy, narrow road with breath-taking views of the Carlingford Lough and the Mourne Mountains. We stopped at a road-side picnic area just outside Carlingford town, in the R173 (Omeath Road). There, we visited an outcrop of metasediments, which had been cleared of vegetation by a geo-conservation volunteer group a few months earlier, and even locals were unfamiliar with them. These rocks form part the promontory where the medieval King John's Castle is located. There are different layers of tightly folded metasediments (mudstone and sandstone), which could possibly be turbidite deposits associated with the closure of the Iapetus Ocean (Fig. 3, *page 123*). There is an unconformity to be appreciated as well, created by a porphyritic intrusion in the Palaeogene, cutting through the Silurian metasediments (Fig. 4, *page 123*), a clear depiction of the 260Ma gap between the events mentioned above. A series of parallel dykes runs towards the centre of the Carlingford Complex in the form of a cone-sheet, in which the country rock has been uplifted.

© OUGS ISSN 2058-5209



Mourne Cooley Gullion Geotourism



Rock Types

- Palaeogene. Granite
- Palaeogene. Dolerite & Gabbro
- Palaeogene. Volcanic Lavas
- Carboniferous. Limestone
- Silurian/Devonian. Granodiorite
- Silurian Metasediments Longford-Down Terrane

Younger / Older

Scale

0 2.5km 5km 10km

European Union
European Regional Development Fund
Investing in your future

This project is part-financed by European Union's INTERREG IVA Cross-border Programme managed by the Special EU Programmes Body

Copyright Government of Ireland, Geological Survey of Ireland. This is based upon Crown Copyright and is reproduced with the permission of Land & Property Services under delegated authority from the Controller of Her Majesty's Stationery Office © Crown copyright and database right 2013 NIMA CS&LA 156. Additional mapping provided by Esri.

Figure 2 Map of the area.

Figure 3 Carlingford Complex: folds in mudstone and sandstone metasediments, possibly turbidite deposits associated with the closure of the Iapetus Ocean.

Figure 4 Carlingford Complex: an unconformity created by a Palaeogene porphyritic intrusion cutting through the Silurian metasediments.

A more impressive intrusion could be seen behind us, in Slieve Foye, the highest point in Co. Louth at 589m, one of the peaks that form part of the Carlingford Complex, and which summit is composed of gabbro.

Our next visit, less than 500m farther on, was King John's Castle, built in the 12th century for the visit of King John of England. The stones used in the building showcase a variety of local stones, such as limestone, metasediments, granite, porphyritic dolerite and basalt, and we could even appreciate some beautiful ripples in the metasediments, inferring that they originated in a shallow marine environment. From this elevated site we could appreciate the medieval walled town of Carlingford with its historic buildings that, apparently, once rivalled medieval Dublin. A good portion of the seafront has been reclaimed by the sea, so the situation of King John's Castle nowadays is not as prominent as it would have been when the original coastline was in place. Carlingford was a strategic and bustling seaport until relatively recent times, and the disused infrastructure can still be found there.

We stopped for lunch in the delightful Ruby Ellen's Tearooms, where they were waiting for us, for our meal was provided by Mourne Cooley Gullion Geotourism. We were all seated in a private room with beautifully arranged tables. Lunch was absolutely delicious, the staff was very pleasant and the place enchanting. Thank you very much, Siobhán!

Whitestown Beach

We arrived at the Carboniferous limestone edge of the Cooley Peninsula to explore some very interesting Palaeogene dykes and other tell-tale features found in the landscape, so much so as to provide us with more evidence of the fascinating geological past of the region.

The first striking fact that we found was the vast amount of rounded pebbles and cobbles representing all the different rocks from the region. There were up to five different kinds of granites, some belonging to the Devonian Newry Igneous Complex, as well as Silurian limestone, Carboniferous chert, and even flint nodules from Antrim. We were walking on the till deposits carried southward during the last glaciation.

We arrived with the low tide and the limestone bedrock was exposed, with a well-defined dolerite dyke cutting through the limestone. The dyke was offset and its ductile movement could be appreciated. Mineral replacement occurred there where the fossils in the limestone were in contact with the dykes (Fig. 5, *overleaf*).

Templetown Beach

A short drive away was Templetown Beach with rather interesting Quaternary cliffs showing very different degrees of deposition. Starting from the bottom, we saw marine muds topped by glacial boulders, and overlain by a silty clay layer. Finally, set back from these deposits, there were several metres of loose

Figure 5 Whitestown Beach: dolerite dyke cutting through the limestone; mineral replacement where the fossils in the limestone were in contact with the dyke.

sands and gravels presenting lamination, channels and cross-bedding. These structures showed particular vulnerability to coastal erosion and, we were told, they were heavily eroded during one week last winter. Siobhán brought our attention to the erosion-prevention efforts taken up by the owners of a cliff house and caravan; the concrete steps built to descend to the beach had been washed away, and the coastal defence seemed hopeless, given the nature of the cliff structures and the location (Fig. 6).

When we looked at the distant shore, we could better appreciate the raised beach, with a flat top levelled with the surrounding land. The presence of raised beaches here are a consequence of the isostatic rebound of the crust after the melting of the ice cap since the end of the last glaciation (Fig. 7, *opposite*).

Windy Gap

Our last stop for the day was the Windy Gap. This place is the result of a fault running NW–SE, breaking up the dykes and exposing the rocks to weathering, and with the scars left by the ice during the most recent glacial periods. The felsic granite here has been intruded by dark mafic basalt (Fig. 8, *opposite*), in the form of the cone-sheet seen in the proximity of King John's Castle.

It is in Windy Gap where the Long Woman's Grave is found, and her legend told in a long engraving on her tombstone. In short, she was a very tall Spanish noblewoman who married a very tall Irish nobleman. Sadly the marriage did not last because she dropped dead when she found out that the man she loved was the lord to only a gloomy hollow in the mountain. (Honestly, not a reason to die, for there are always to new lands to see and to possess; but that's my opinion, for I myself have traded Spain for Irish lands without regrets!)

Figure 6 Quaternary cliffs at Templetown Beach.

Figure 7 Distant view of the raised beach from Templetown Beach.

It is only a short walk from Long Woman's Grave to the quarry used to extract the stone to build the walls. The rock there is microgranite from the Carlingford Igneous Complex, and it has the peculiarity of being very lightweight.

With this, we concluded the outings for the day and we returned to the Carrickdale Hotel, where we had dinner and a good time together before breaking up for the night.

Sunday 7 September

The day started bright and dry. We met again at the Carrickdale Hotel car park with Dr Power. Siobhán took us to the Slieve Gullion Forest Adventure Park, where we met with more attendees, before driving up to the mountain.

Slieve Gullion Ring Complex

We departed from the Slieve Gullion Forest Adventure Park and continued on the road through the forest and up to the west side of the mountain, where we were treated with the gorgeous view of the landscape and, in particular, with the entire western view of the ring-dyke.

The Slieve Gullion Ring Complex is a Palaeogene intrusion, formed about 58Ma ago, and it is believed to be the remnants of a huge volcano with a violent history, in which the magma chamber eventually collapsed, leaving three distinct units to be appreciated today. The ring-dyke is one of the units, and it was emplaced into the Devonian Newry Igneous Complex and the Silurian metasediments. At 11km in diameter, it is believed to be the margins of the collapsed caldera. The rocks here are mainly porphyritic felsite, but vent agglomerates can also be found on the south-west section in locations such as Forkhill Quarry, though we did not visit it. Slieve Gullion itself, the second unit, is situated on the central part the ring-dyke complex, and it is a slightly younger intrusion of alternating layers of felsic and mafic rocks. Finally, the third unit can be found at the south-east of the ring, where granophyric microgranites form the Claremont Mountain. The bedrock under the green fields between Slieve Gullion and the ring-dyke is granodiorite from the 400Ma old Newry Igneous Complex.

As mentioned earlier, the Ring of Gullion was the first ring-dyke to be described. Its study has been of great importance, as it helped with the identification of similar structures elsewhere around the world. Siobhán mentioned that there are other interpretations of this structure, proposing that it is not a ring-dyke, but rather an intrusion sheet that has eventually eroded.

Figure 8 Felsic granite here has been intruded by dark mafic basalt at Windy Gap.

Figure 9 Outcrop revelaing some of the different layers within the body of the granite of the Slieve Gullion Ring Complex.

Moving on to other features in the landscape, we could appreciate some vertical faulting within the ring-dyke. Cam Lough, found within a glacier-carved valley, owes its crooked shape and emplacement precisely to the fact that a major fault cuts through the dyke and surrounding rocks here, where the subsequent action of the ice in the weaker rocks was responsible for the shaping up of this area.

We made our way down, diving through the alternating felsic and mafic layers, as well as some brecciated sections. Siobhán pointed that there are 18 different layers in Slieve Gullion, and among them, green dolerite and gabbro can be found. We made a stop beside an outcrop by the road, where we could observe different layers within the body of the granite (Fig. 9), with distinct coarse- and fine-grained quartz and feldspar crystals. After this stop, we left the western parts of the region to reach the Mourne Mountains, but not before driving through Drumlin Country.

The Mourne Mountains Complex

There are five different granites in the Mourne Mountains Complex, all dating 56Ma. They were denominated G1, G2, G3 and G4 by James Ernest Richey (1886–1968), from oldest (G1) to youngest (G4); later, a new division was made in G4 to distinguish the finer granites of G5. All five granitic intrusions were emplaced over Silurian metasediments in a series of dyke-swarms and surrounded by a single inverted cone-sheet, with a dip of 35˚ towards the granite and a calculated focal point of 3km in depth. The emplacement of these granitic rocks occurred in five phases, divided into two centres — the Western Mournes Centre and the Eastern Mournes Centre. We drove through the Western Mournes, composed of G4 and G5 granites, on our way to Spelga Dam in the central part of the Mournes. Being an early September Sunday morning, we encountered a lot of tourists, and we were warned that we would see more in Newcastle, a leisure town for Belfast folk on weekends.

The Mourne Mountains area is linked to a gold controversy; still much debate is going on as to whether its occurrence was real, and the fact that Ireland's Bronze Age Gold has been traced to this area. The missing piece of the puzzle is that the source of gold cannot be found, despite of being told that we could pan the nearby river and find gold speckles!

There is also a water story associated with the Mournes, which Siobhán included in her explanation. There are a number of reservoirs in the Mournes thanks to the glaciated landscape and the impermeability of the granites, although the Spelga Dam is actually surrounded by metasediments. But a highlight in this water story is, without a doubt, the Binnian Tunnel, running underneath several mountains. This is an outstanding engineering endeavour that was opened in 1952. It has the purpose of collecting the run-off rainwater from the mountains as well as diverting some the water flow from the Annalong River onto the Silent Valley Reservoir. A 22 mile wall was also built around the peaks to mark the boundary of the water. The Spelga Dam was low at that time of the year due to the lack of snow during the previous winter and spring, in addition to a dry summer.

Coming back to the granites, we examined each of the five different types of rocks. Starting with the oldest granites in the Easter Mournes Centre: G1 is feldspathic granite, G2 is quartzose granite and G3 is aplitic granite. As for the rocks in Western Mournes Centre, we find G4 as pink granite, while G5 is blue-greyish granite. All of them, except G1, present drusy cavities in the roof zones, in which rare minerals like topaz, beryl and fluorspar, among others, have been found. During the intrusion, exsolved gases were trapped in the upper levels to form these cavities. We did not directly observe any of the granite facies, although at a later stop we found plenty of all of these different rock types in a beautiful conundrum by the beach.

After this stop we drove east towards Newcastle, where we had lunch; though being such a busy day in Newcastle and having misunderstood Siobhan's instructions, the group got separated to opposite ends of the town. We regrouped at Bloody Bridge River car park, where we were told the geological history without visiting the outcrops, as we would have needed half a day just to enjoy the hike and the geology.

Bloody Bridge River

This place owns its gloomy name for being scene of a massacre in 1641, when the water flow turned red from the spilled blood of the victims. The Mourne Mountains drop down towards the sea at this point. There are plenty of exposed metasediments and granites, as well as contact metamorphism of sediments forming hornfelses; in addition there are some roof metasediments on the top of the surrounding mountains. There are also glacial deposits and the glaciated valley, cut very deep by the river. In this area, the inverted cone-sheet surrounding the Mournes granitic intrusions runs parallel to the seashore. But in order to appreciate this feature better, we moved to our next and last stop.

Before we left the car park, however, we appreciated the sculpture there: two peculiar, sinuously shaped rock columns by artist Ralf Sanders called *The Smuggler's Head*. When properly positioned in front of the two rocks, the empty space between them reveals the shape of a smuggler's head (Fig. 10, *opposite*). The idea behind this sculpture is that 'a good smuggler must become almost invisible — hidden and become part of the landscape'.

Figure 10 Stone sculpture entitled The Smuggler's Head*, by Ralf Sanders (Photo credit: Mourne Heritage Trust © 2015).*

Figure 11 Conundrum of rocks at Glasdrumman Beach, Co. Down, with Silurian metasediments (foreground), Mournes granites (centre and background) and basaltic cone-sheet (dark rock in centre).

Glasdrumman Beach

Our last stop was Glasdrumman Beach, where we found no other visitors than ourselves. The beach is a beautiful conundrum of all rock types, with an impressive exposure of the basalts belonging to the inverted cone-sheet, as well as the Silurian metasediments, and most of the five types of granites from the Mournes and metamorphic hornfelses. Because of erosion, some structures are true sculptures shaped by the force of nature (for example Figs 12 and 14). I think it is best to represent what we saw at the beach by simply showing some of the most remarkable outcrops (Figs 11 to 16, *pages 127–8*).

After a leisurely investigation of the outcrops, our trip was concluded and Susan Pyne thanked Dr Power for offering us such a pleasurable geology weekend.

I would like to thank everyone who came along for making this weekend so enjoyable with your attendance, and to Dr Power for showing us the area and showering us with all her knowledge, as well as joining the OUGS (yes!) (Fig. 17). A friendship has also been born as a result of this weekend (thank you Siobhán), and we look forward to returning soon to the fantastic Mourne Cooley Gullion region to celebrate its promotion to the status of GeoPark!

Figure 12 Metasediments, basalt and granite assortment at Glasdrumman Breach.

Figure 13 Basalt cone-sheet at Glasdrumman Beach, that could be seen exposed in a discontinued fashion at certain points on the beach.

Figure 14 Eroded shapes in the granites at Glasdrumman Beach.

Figure 15 Silurian metasediments at Glasdrumman Beach.

A note about the Mourne Cooley Gullion Geotourism

The Mourne Cooley Gullion Geotourism project is an INTERREG IVA-funded project aimed at promoting a new geotourism destination, increasing geoscience education in and about the region at all academic levels, and applying for Geopark status. The island of Ireland already has three Global Geoparks: Marble Arch in Fermanagh and Cavan, The Burren and Cliffs of Moher in Co. Clare and Copper Coast in Co. Waterford. By 2015, Geoparks will have full UNESCO status, equivalent to the World Heritage Sites.

Geopark status is awarded to areas around the world with geological heritage of international significance. A Geopark is about celebrating that geological heritage, communicating the geoscience knowledge and ideas to the public in an engaging way, and contributing to sustainable economic development. Geoparks are as much about people, their local heritage and ways of life as they are about rocks. Apart from rivers, coasts and mountains, Geoparks do not have physical boundaries and they are community-led rather than being managed by an outside body.

Reference

Baxter, S. 2008 *A Geological Field Guide to Cooley, Gullion, Mourne and Slieve Croob*. Louth County Council & Geological Survey Ireland — online (accessed 9.01.2015)

Figure 16 Porphyritic granite in contact with basalt at Glasdrumman Beach.

Figure 17 The field trip attendees in front of the granite outcrop, Slieve Gullion Ring Complex.

Jurassic Ark — an exhibition at the Bath Royal Literary and Scientific Institution (BRLSI)

Rich Blagden and Rosemary Darby

[combined and edited by David M. Jones] [photographs by Rich Blagden]

'Jurassic Ark' was an exhibition held last summer up to September 27, 2014. At least two OUGS Members — Rosemary Darby and Rich Blagden (both members of our South West Branch) — visited the exhibition and wrote to me about it. They kindly agreed to my suggestion that I edit their two texts together as a short report for all to read. Rich also provided a number of photographs.

This exhibition featured spectacular fossils from an ancient Somerset sea (Fig. 1).

The fossils were collected from the Lower Jurassic rocks of Strawberry Bank, Ilminster by Victorian geologist Charles Moore, who lived first in Ilminster and later in Bath. Moore had been watching two boys rolling a limestone nodule around near his home when the rock split, revealing a beautifully preserved fossilised fish inside. Realising the potential of his find, Moore scoured the local quarries until he found the layer in a quarry at Strawberry Bank, and over the next few years collected thousands of specimens.

Figure 1 Looking into the mouth of a fish that died 181 million years ago.

His collection was first displayed at BRLSI in the 1850s and was purchased by the institution on his death in 1881. Since then, however, the collection was almost forgotten until part of it was rediscovered in 2011. Moore had logged and labelled his specimens meticulously, and many had not been unwrapped since they were labelled and stored by him. The collection has now been fully catalogued and is being studied at Bristol University.

Part of the reason for the interest is the impeccable condition of many of the specimens. These creatures lived in the waters of a lagoon, with sheltered conditions and a lack of movement, making the water highly stratified. The bottom layer was thus hypoxic and hypersaline, so if corpses made their way to the bottom of the lagoon they would effectively be out of reach of scavengers. Decay was very slow, but bacteria that formed in the first week or so would give off ammonia, which reacted locally with bicarbonate and calcium ions in the water, directly precipitating limestone over the body. In some cases, before long a thick, hard limestone nodule that resisted crushing by overlying strata would surround the whole corpse. The nodules themselves were buried in a 150mm layer of calcareous mud, and thus remained impervious to damage for 181 million years until Moore's chance discovery.

The exhibition itself was small and contained just a fraction of Moore's collection, but the quality of his specimens is extraordinary (Fig. 2, *overleaf*). One can only imagine Moore's reaction to splitting open a nodule and discovering a fish, mouth still full of teeth and hanging open as in death, preserved in such remarkable detail that every scale is faithfully recorded (Fig. 3, *page 131*). "I [Rich Blagden] have seen fish in worse condition on a fishmonger's slab."

Rich noted the excellent sketches that complemented the exhibits. Rosemary reports that a booklet was available, the pages of which were reproduced on large panels at the entrance to the exhibition. The BRLSI welcomes children and runs frequent activity sessions for them, and at this exhibition provided worksheets for primary-school-aged and older children.

Noting the lack of a map indicating the position of Ilminster in Somerset, or Strawberry Bank and the position of the quarry, Rosemary suggested that the BGS might be able to help. However, it seems that the actual quarry site is not known and may have been built over since Moore's time.

The recent Jurassic

The first panel showed the timeline from 4560Ga, the Hadean to the present, and included illustrations of Society specimens from the Krasnoyarsk Pallasite c. 4.2Ga and later, and a large ammonite.

Worlds apart

The second panel showed the splitting of Pangaea and the movement of the locality of Ilminster from around 36°N to 50.9°N.

Life in the Toarcian

The third panel described the plants, animals and insects on land and in the seas of the time.

Found, forgotten, reappraised

The fourth panel provided a brief biography of Charles Moore, and included a representation of the hand-drawn section of Mid- and Upper Lias layers in the quarry, with his logging of the specimens as he had found them.

© OUGS ISSN 2058-5209

Understanding lost worlds

The fifth panel was a description of the project to find and display the specimens. Some were already in the BRLSI scientific collection, others were found in the Somerset heritage collection. The specimens, wrapped in newspaper from 1863, were stored in strong soap-boxes and other product boxes.

The Strawberry Bank Lagerstatt

The sixth panel demonstrated how the rapid encasement of the specimens in limestone had preserved many soft parts and the 3D structure — as described above.

Near this last panel there was a cabinet containing a photograph of some of the boxes in which Moore kept his specimens; and some of these boxes (e.g. a 'Frys Homeopathic Cocoa' box) and the newspapers he used were on display (worthy of the conservator's art, although they may be replicas). There was also a complete nodule and a revolving stand under a microscope, showing bits of limestone with dragonfly, grasshopper wings and coleoptera remnants, demonstrating how carefully Moore had examined the rocks he collected.

The fossils themselves were displayed in cases of various sizes.

There were six cases demonstrating the range of 3D specimens, all of which had been meticulously extracted from their limestone casing by scientists at Bristol University. These included several juvenile marine animals, suggesting they may have been in a 'nursery' lagoon (Fig. 4, *opposite*); there was also a female with embryos visible. One fish has had a bite taken out of its back by a predator or scavenger. Another has its guts trailing out (Fig. 5, *opposite*). Others have the soft membrane under the gill covers preserved beautifully (Figs 6 and 7, *page 132*).

Large white wall hangings showed, in black and white sketches, a labelled scene with brief descriptions.

(a) *Prey and predator* with a *Pelagosaurus*, squid and fishes;
(b) *Island life*, a swampy area with various trees, a 'crocodilian' and many flying insects;
(c) *Fossilisation and preservation* of a large fish, with, in a case below, the 3D fish in its nodule, with fins and scales — a demonstration of the care with which each specimen had been liberated from its preserving limestone nodule. "I [Rosemary Darby] think congratulations are due to the lady shown in Panel 5 (*see above*) working with a drill."

Elsewhere in the exhibition there were three young icthyosaurs, a few of the rare examples found preserved with their skulls in three dimensions, rather than flattened, and with the sclerotic rings in their eyes intact. These are of particular interest to members of the Bristol University team of investigators, because with micro-CT scanning they can model the 3D structure of these ancient creatures' skulls. Fish and icthyosaurs make up the majority of the exhibition space, although there are also some excellent *Pelagosaurus* fossils (Fig. 8, *page 132*) and even some tiny dragonfly wings and beetle carapaces.

'Jurassic Ark' was part of the Jurassic Ecosystem of Strawberry Bank Ilminster (JESBI) project, which is a collaboration between Bristol University and BRLSI, and which occasionally appears at other events in the Bristol area. For more information see the JESBI pages at http://www.brlsi.org/museum-collections/jesbi. Further information on Charles Moore can be found at www.google.co.uk/?gws_rd=ssl#q=Charles+Moore+fossils

Acknowledgement

Thanks are due to BRLSI for allowing photography. We have sent a copy of this report to **admin@brlsi.org.**

Figure 2 Fossilised fish from the Jurassic Ark exhibition.

Figure 3 Almost perfect preservation, including the detail of every fin, scale and head part.

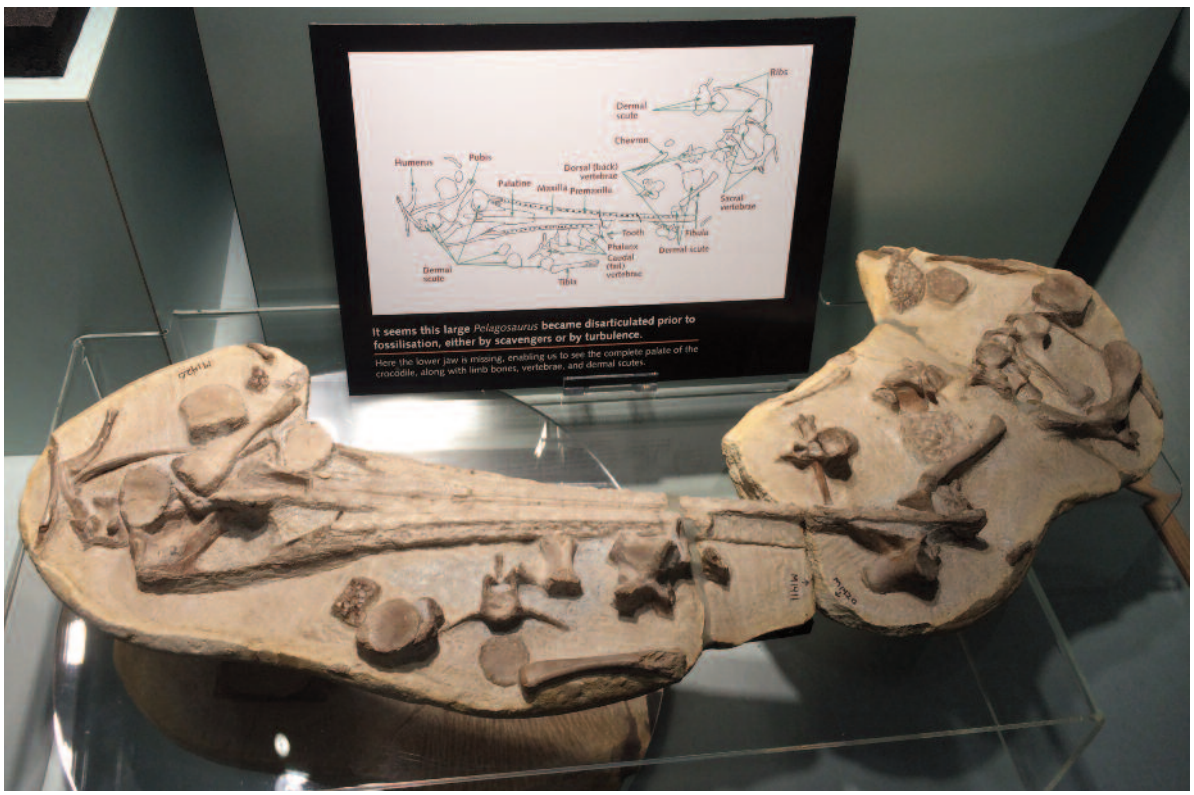
Figure 4 Infant ichthyosaur, Stenopterygius triscissus.

Figure 5 Fossilised fish showing preserved gut, lower left.

Figure 6 Soft membranes of the gill covers and abdomen preserved in a Pachycormus *fossil.*

Figure 7 Pachycormus *tail fin.*

Figure 8 Disarticulated Pelagosaurus.



Editor's notes to contributors

Following are guidelines for the submission of articles to the *Proceedings of the OUGS*. The principal theme encompassed within these guidelines is 'please keep it simple'. Let your editor do his job and please do not try to simulate, emulate or reproduce the page layout of the *Proceedings*. I have dedicated page-layout software (QuarkXPress) to do this and any special formatting, special characters and embedded illustrations that you include in a word-processing document can be lost (at best) or seriously confuse and crash (at worst) my iMac or the QuarkXPress software when I import it into the layout.

If your article contains special characters (such as mathematical symbols), please draw these to my attention — I will probably spot them anyway — so that I can import them properly with the glyphs menu in QuarkXPress.

Here are the basic guidelines. I will contact you about any queries that arise when I read your article. I will send you an edited version, showing you any changes that I have made and raising any queries or requesting any missing information.

Guidelines for *OUGS Proceedings* articles

As *OUGS Proceedings* Editor I do not want the publication of your article to be more work than is necessary for you (or for me!). Your article need not be more than about 1,500 to 4,000 words in general, but I leave the length up to you to suit the material you are writing about.

Regarding articles from the presenters of lectures at the OUGS Symposium, all OUGS members are grateful to you for presenting a talk at the OUGS Annual Symposium, and for agreeing to submit a version of your talk for publication in the *Proceedings*. The purpose of this is to make your information available to OUGS members and others who could not attend the symposium. As OU students and OUGS members we enjoy hearing and learning the information these symposia bring to us.

All that is necessary are:

• A Word (or compatible) file of the text: There is no need for you to attempt to format the text in any way using tools in Word or other word-processing software. I will do the page layout format in the *Proceedings* house style, using dedicated publication-industry-standard page-layout software (QuarkXPress). However, feel free, if you wish, to use **bold** and/or *italics* to indicate headings and subheadings so that I can set these into house style.

I do not require a hard copy, but if you need to point out special characters or attributes in your paper, it may be a good idea to send one with these items marked up or otherwise highlighted. Otherwise I can accept electronic files attached to an e-mail, or files on a CD.

• Each illustration, chart, graph, map or other illustration as a separate digital file in high resolution: 300dpi minimum for colour or half-tone images; 1200dpi for line illustrations. Tables composed in Word or Excel are fine, as they are just text. A rough guide to the number of figures in an article is 10 to 30. Obviously as a symposium presentation speaker you might have shown numerous slides, so please use your best judgement on the number to include with the paper to be published — again usually 10 to 30 is only a rough guide.

• Please be sure that we have permission to publish any illustrations that are not yours: Also, please give me the appropriate information to cite in acknowledgement in the figure caption; and please tell me in writing or in an e-mail message that you have obtained the permission necessary for each illustration in your article that is not yours.
As the author, this responsibility is yours.

• Please do *not* embed your illustrations in Word picture boxes within the text: All that is necessary is to indicate, by a reference within ( ) or within [ ] in your text, where the illustration should go.

• You can submit the material as attachments to e-mails to me or send it to me on a CD: I am on BT Broadband, so I can receive large files. It is usually best to attach only a few illustration files each to several e-mails. This applies especially to large files of photographs, charts and graphs. Alternatively, a digital sharing package can be used, such as Dropbox or similar.

• Where appropriate, cite your sources, or make it clear that a statement is a supposition, or solely your own view or opinion. We use Harvard style citations in the text: (author date, pages), e.g. (Jones 2004, 51–3); and your sources or references should be listed in alphabetical order by author and date at the end of your article. You need to list the author, date of publication (or of access to a website), full title, periodical volume and number, or place of publication and publisher, and page numbers.

If you miss out anything, I will ask you for it.

If your list includes items not cited in your text, it will be called 'Sources'; if all items in your list have been cited in your text, it will be called 'References'.

That really is it! The editing and page layout are my job, so let me do it for you. I will communicate with you as necessary as I do this, with queries or difficulties with any formats, special symbols, characters, etc, as is the task of any editor.

For you really keen authors, regarding grammar and spelling I use:

Butcher, J. 1992 *Copy-Editing: The Cambridge Handbook for Editors, Authors and Publishers* (3rd edn). Cambridge: Cambridge UP

The Oxford English Dictionary

The Penguin Spelling Dictionary 1990. London: Penguin Books Ltd

Ritter, R. M. (ed and comp.) 2000 *The Oxford Dictionary for Writers and Editors* (2nd edn). Oxford: Oxford UP

Ritter, R. M. (ed and comp.) 2002 *The Oxford Manual of Style*. Oxford: Oxford UP

Please contact me at any time about your paper:

Dr David M. Jones, *OUGS Proceedings* Editor, 41 Blackburn Way, Godalming, Surrey GU7 1JY; 01483 424308;
proceedings@ougs.org OR **ce.ocelotl@btinternet.com**

The Open University Geological Society (OUGS) or its Proceedings Editor, accept no responsibility for breach of copyright. Copyright for the work remains with the author but copyright for the published article will be that of the OUGS.